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TECHNICAL REPORT

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AN ESTIMATE OF SOVIET TECHNICAL CAPABILITIES IN SOLID-STATE RESEARCH BASED UPON SOVIET PUBLICATIONS IN THE SOLID-STATE ELECTRICAL DEVICE FIELD

PROJECT NO. [illegible]974

[illegible] JULY [illegible]

AIR TECHNICAL INTELLIGENCE CENTER
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TECHNICAL REPORT NO. TR-EL-5

AN ESTIMATE OF SOVIET TECHNICAL CAPABILITIES IN SOLID-STATE RESEARCH BASED UPON SOVIET PUBLICATIONS IN THE SOLID-STATE ELECTRICAL-DEVICE FIELD

PROJECT NO. 9974

31 JULY 1953

Prepared by

BATTELLE MEMORIAL INSTITUTE
COLUMBUS, OHIO

for

AIR TECHNICAL INTELLIGENCE CENTER
WRIGHT-PATTERSON AIR FORCE BASE
OHIO

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SUMMARY

Purpose

To estimate Soviet technical capabilities in solid-state research by (1) considering Soviet publications in this field and (2) evaluating the results of these considerations in terms of the status of solid-state research in all other countries publishing work in this field.

Factual Data

The study of Soviet literature in the solid-state electrical-device field was carried out in the following manner. The Soviet journals corresponding to electrical engineering, physics, and physical chemistry were investigated with the aim of obtaining a satisfactory sampling of literature. The literature items were collected and organized into a bibliography containing 523 listings for the period between approximately 1940 and 1950, according to a modified breakdown of the World-Wide Digest of Literature on Semiconductors published by Battelle Memorial Institute. The complete Bibliography is included at the end of this report. A study of the occurrence of literature items in various journals is found in Section III. The various types of interpretations of the literature are found in Section IV.

Attempts were also made to find patent literature. It was discovered that the U.S.S.R. has no patents, but does have engineering standards which appear to be substitutes. No patents were obtained during this survey, although the Library of Congress was discovered (too late for this report) to be a possible source of them.

Subsequent to collecting and organizing the literature, several types of analyses were conducted:

(1) In an attempt to find out roughly the type of coverage of literature in the Bibliography, an analysis was made of the Bibliography relative to its outline, which, it will be recalled, was the outline for the Digest of Literature on Semiconductors, modified somewhat. In particular, special attention was given to omissions or concentrations of literature within this outline.

(2) To obtain some ideas about the quality and the coverage of Soviet work, as well as the type of equipment and instruments used, a digest of selected abstracts of about 200 articles of literature was made. Here again, the outline of the bibliography of the Digest of Literature on Semiconductors was used as a guide in classifying the literature references.

(3) To obtain a more detailed analysis of the literature, a few complete articles were studied and thoroughly criticized.

In addition to making a thorough analysis of the literature for establishing ideas concerning nature, quality, and coverage, attempts were also made to measure the capability of the Soviets through consideration of the important men in the solid-state electrical-device field, on the basis of the number of their publications and the technical status of their work. It was hoped that some idea of whether mass movements of men from one field of research to another occurred during the period of investigation, and, still further, whether information on new men coming along would be provided.

The current status of the U.S.S.R. and the U. S. was prepared, using as a yardstick the Literature Digest, the historical data, and the various literature and personality analyses.

The total picture obtained was analyzed, and attempts were made to estimate Soviet capabilities now and their rate of advance at the present time and in the future.

This report was prepared by A. E. Middleton, E. F. Conran, and J. E. Davis, Battelle Memorial Institute. The comments made herein are based on information available as of July, 1952.

Discussion

In order to analyze the status of solid-state research in the U.S.S.R. from considerations of Soviet publications, an intimate understanding of the nature of solid-state research and the behavior of solid materials is necessary. The discussion in Section I, which attempts to provide such an understanding, leads to the conclusion that solid-state electrical-device research is the leading phase of solid-state research currently giving new information concerning the behavior of solids.

The manner in which solid-state electrical-device research evolved and the world-wide political events which may have placed restrictions on local publications indicated that a survey of Soviet literature for the period from 1940 to 1952 would be necessary in order to avoid obtaining a warped picture of the capability of the U.S.S.R. in solid-state research. These considerations also indicated that the best evaluation of the capability of a country in solid-state research could be obtained by surveying all the basic and applied work done in the solid-state electrical-device

field. Therefore, it was decided to restrict the literature studies of the subject survey to this phase of solid-state research.

Solid-state electrical-device research is a hybrid field involving chemistry, physics, and electrical-engineering aspects. Actually, if all electrical, optical, and magnetic parts of solid-state-physics researches having any basic or practical value were singled out, the scope of solid-state electrical-device research would be outlined. The field has materials, properties, and device aspects, with applied and basic sides to all three areas. All materials are classified in one of the following categories: metals, transition materials, semiconductors, and dielectrics.

Solid-state electrical-device research did not exist prior to 1934. In general, fully initiating it required (1) the development of quantum mechanics, (2) the growth of the electronics industry, and (3) definite recognition that many materials exhibit many of their electrical and optical properties due to imperfections in crystals. All these conditions were fairly well established about 1940. In order to provide some estimate of the relative status of solid-state research, and specifically solid-state electrical-device research, in the major countries of concern, namely, the U. S., Germany, and the U.S.S.R., before and around 1940, a special historical study was conducted.

Intimate knowledge of the nature of the solid-state electrical-device field led to the conclusion that the status or capability of an organization or country in this field could be basically determined by (1) the extent of its ability to make crystalline materials of any of the types of transition materials, semiconductors, or dielectrics with controlled

amounts and types of impurities and imperfections, (2) the amount of collected information on electrical, optical (also X-ray), and magnetic properties of these synthetically produced materials, and (3) the ingenuity and precision demonstrated in using the materials and their specific characteristics in developing solid-state devices.

For establishing a useful comparison of the nature and amount of work currently being done in the solid-state electrical-device field in the U.S.S.R. and the U. S., the Digest of Literature on Semiconductors, published each year by Battelle Memorial Institute, proved to be very helpful. Also, its outline was adopted for use in arranging Soviet literature in the Bibliography. Further, the Digest yielded information on the over-all quantity of unclassified literature in the semiconductor section of the solid-state electrical-device field.

The various survey articles concerning early work in the solid-state electrical-device field and associated types of research, discussed mostly in Appendix I, indicate that around 1940 Germany and the U.S.S.R. were leaders in this field. For example, Sominsky reports, in 1940, that A. F. Joffe was head of an institute which had sections called Electrophysics, Molecular Physics, and Nuclear Physics. Electrophysics was the heading used for solid-state research and applications in electrical fields. There were 17 laboratories making up the three groups. These included (1) the semiconductor laboratory, headed by A. F. Joffe who, up to this time, had investigated 220 combinations of semiconductors in regard to the effects of strong fields on electrical conductivity, as well as many other properties, (2) the cuprous oxide rectifier laboratory, (3) the selenium

rectifier laboratory, (4) the copper sulfide rectifier laboratory, (5) the thallium sulfide photocell laboratory, and (6) the dielectrics laboratory, including plastics and rubber, as well as ceramics. The future aims of this Soviet solid-state research group in 1940 were (1) to attempt to perfect photocells and rectifiers developed by the institute so that they could be put into general use, (2) to create high-current thermoelectric apparatus and sensitive receivers of radiative energy, and (3) to develop theories of rectification, photoeffects, and thermal effects.

Specific evidence of the strong leadership of Germany in this field about 1940 is recognized when a German work plan for the field of semiconductors and allied fields, written in 1944-1945 at the Osram Company in Germany, is considered. This program is included in Appendix I and is entitled General Program Suggested for Application of Semiconductors Based on Scientific Considerations. The amazing conclusion that can be drawn, after examination of this work plan, is that much of the work accomplished during the past six years, from 1946 to 1952, in the U. S. is predicted by this outline. New developments, such as the transistor, electroluminescent plates, thermistors, new catalysis methods for solid-state studies, new rectifiers (dry-disc and diode types), electrostatic clutches, high-temperature rectifiers, semiconductive cathodes, new infrared photocells, and low-noise-level and low-temperature-coefficient high-stability resistors, are all indicated as possibilities in this outline. However, it will be particularly noted that ways of achieving these practical applications are not suggested; this indicates that the Germans were fully cognizant of the practical possibilities in this field, but probably had not achieved them in practice.

The U. S. was definitely following the leaders in the solid-state electrical-device field in 1940. It was not until about 1942 that considerable effort was applied by the U. S. in this field. It must be remarked here, however, that much unpublicized work was going on in this field behind industrial doors. In particular, the work at Bell Telephone Laboratories is believed to have ranked as high as that in Germany and the U.S.S.R.

The status in 1950 and 1951 can be estimated by studying the World-Wide Digest of Literature on Semiconductors prepared by Battelle in both of these years. Although these Digests do not include work on dielectrics or on metals and alloys, the nature of the solid-state electrical-device field is such that these omissions in the Digests represent only a minority of the total literature in this field. An analysis of the Digests reveals the following:

(1) Approximately 7 per cent of the literature in 1950 and 1951 was of Soviet origin.

(2) Apparently no work was being done in the U.S.S.R. in 1950 and 1951 (at least none was published) on the "Group IV" elements, namely, silicon and germanium.

(3) The outstanding developments in this field which were of practical value were concentrated in the U. S. literature. Also, most of the advances in the fundamental understanding of the behavior of solids were attributed to others than the Soviets. One exception is the Polaron Theory of Solids developed by S. I. Pekar and associates.

Briefly, from this one examination, it would appear that the U. S. is leading the solid-state electrical-device field in all aspects (materials, properties, and components) at the present time.

With due consideration to the most desirable type of breakdown for the Soviet literature, it was decided to use the outline of the Digest of Literature on Semiconductors with some additions. Organizing the large sampling of Soviet literature for the years from 1940 to 1951 into an outline like that of the Digest of Literature on Semiconductors, and subsequently charting the occurrence of literature in each year in each of the principal categories of the outline in Section III, revealed the following:

(1) Except for a few mining, metallurgical, and strictly chemical articles on germanium and silicon, no consideration had been given by the Soviets to materials in the fourth group of the atomic table throughout the entire life of the solid-state electrical-device research field.

(2) As is obvious from Table V, Section IV, the number of publications as a function of time from 1940 to 1951 follows more or less an expected trend, assuming adequate sampling and no Soviet classification of literature, except for the fact that in 1950 and 1951 there was an anomalous drop in the number of literature items in the field. This study, therefore, points out that the more recent years from 1949 to 1951 are probably the least reliable for drawing conclusions on the basis of open-literature publications. The explanation of this drop-off is probably classification of literature. Apparently, the Soviet stoppage of publications leaving the U.S.S.R. has provided, in part, the censorship they desired.

(3) This mechanical examination of the Soviet literature in a bibliography arranged according to the outline of the <u>Digest of Literature on Semiconductors</u> also indicated that the Soviets have apparently directed their activities in the field of solid-state research over a rather broad region during the last 11 years. They seem to be strong in research on the theory of conduction in solids and in studies of photoconductivity, phosphorescence, and dielectrics, particularly titanates. Also, they appear to be strong in some phases of rectifier research, mainly those dealing with selenium and compound semiconductors, such as copper oxide and copper sulfide. Magnetic effects in intermetallic compounds and semimetals have also been considered. There is evidence in very recent literature that the developments outside the U.S.S.R. are influencing the emphasis of their present work. Specifically, there are indirect indications that they are beginning to investigate the fourth-group elements, germanium and silicon, and to consider problems related to transistors.

Section VI is devoted to a study of important Soviet personalities, their specialties, and their locations, as far as could be determined. Their specialties were assumed to be in the field in which they consistently published. This assumption is apparently valid in that the Soviets having so-called fringe specialties to the field of solid-state electrical devices have been identified, such as those working primarily in chemistry and crystallography. The method of listing used in Section VI is also applicable to the identification of secondary authors.

It will be found that 3[illegible] outstanding personalities were segregated according to eight major fields of interest (based on the

period from 1940 to 1951). Obviously, the youngest group of present leaders will not be fully represented by this list. Exhibits A and B of Section VI list the personalities in alphabetical order and by fields, respectively. The list of outstanding personalities forms a convenient record, while the longer list, based on the principle that anyone having three or more publications is a personality to record, provides a "watch list" of persons who may be future leaders in the field and includes those who have recently become leaders. This list may, therefore, be of considerable interest in the years to come.

Out of this combined study of the biographical register and the bibliography of Soviet literature, it was also possible to obtain some information on research institutions which are outstanding for the work done in this field. It appears that the facilities of prime interest are the following:

(1) Physics Institute imeni E. N. Lebedev, Moscow

(2) Leningrad Physico-Technical Institute

(3) Institute for Physical Problems, Moscow

(4) Ukrainian Academy of Sciences, Kiev

(5) Mathematics Institute imeni V. A. Sokolov

(6) Institute of Crystallography, Moscow

The first four of the facilities listed are well-known centers of solid-state electrical-device work. From the source location of a telegram sent by Vavilov of the U.S.S.R. to the International Conference on Semiconductors in Reading, England, in 1950, it was noted that the headquarters for semiconductor and electrical-device research is probably at the Leningrad

Physico-Technical Institute. The last two represent facilities which do associated work pertinent to the field of solid-state electrical devices.

The above type of study resulted in considerable information on the nature of Soviet solid-state research. Nothing regarding the quality of work was obtained, however. This required an entirely different approach. In order to obtain real insight into solid-state electrical-device research and the general status of solid-state research in the Soviet Union, it was necessary to carry out a rather intensive study of the quality of the Soviet literature. This was also required in order to estimate, in a general way, the types of laboratory equipment. Furthermore, it was hoped that, indirectly, such a study, as a function of time, would provide some estimate of the magnitude of operations in the solid-state research field.

The digest of Soviet literature on solid-state electrical-device research for the period from 1940 to 1951, which is embodied in Section IV, reveals that the Soviets do not show any evidence in their open literature of having practical transistors, phototransistors, high-voltage diodes, electroluminescent plates, or high-temperature rectifiers. However, they do show evidence of having thermistors, new photocells, thallium sulfide photocells, new phosphors, and piezoelectric materials, namely, barium titanate. Further, it can be said, comparing this digest with the World-Wide Digest of Literature on Semiconductors (and other information on U. S. work), that the literature of today in the field of solid-state electrical devices shows the U. S. to be far ahead from the practical-device-development standpoint.

From a study of some 15 translated articles, as well as the digest of Soviet literature, it was concluded that the Soviet investigators showed a competence and originality comparable to that of workers in similar fields anywhere else in the world. It was more or less expected that this would be true in view of (1) their excellent start in the late 1930's and the early 1940's, as indicated in the outline of work presented by A. F. Joffe[1] in 1941, and (2) the probable availability of the work plan of the Osram Company to the Soviets in 1945. In view of this revelation, some reason other than poor quality of work is necessary in order to explain the obviously greater progress of the U. S. in this field over that of the Soviet Union.

In looking for reasons why the U. S. is apparently leading the U.S.S.R., it is of prime importance to recognize that progress in the field of solid-state electrical-device research and solid-state research is measured by the degree to which materials control is achieved. It should be emphasized that improved control of semiconductor materials is an absolute necessity to ensure fundamental advances in understanding the behavior of solids. Examination of the Digest of Literature on Semiconductors for 1950 and 1951 reveals that great strides were made, particularly by the U. S. and the United Kingdom, in regard to controlling semiconductors, and impurities and imperfections in them. As a result, a better understanding was gained of the reasons for their electrical properties and how to modify them, including how to set up particular geometrics to achieve particular types of electrical space charge within single crystals. It can be said that achievement of this type of control of materials was a spectacular advance and must not be underestimated in regard to the difficulties

(1) Semiconductors and Their Technical Application, A. F. Joffe, J. Phys., U.S.S.R., 1941, Vol 4, p 169.

encountered in achieving the advance. Further, it can be considered the very heart of what is necessary in order to realize applications such as were indicated in the outline made by the Osram Company in Germany in 1944 to 1945. It should also be recognized that the great success of the U. S. in this field is a direct function of the tremendous rise of the electronics industry during 1940 to 1950, and of the evolution of a large number of teams working on all aspects of semiconductors throughout the nation in industry and associated laboratories.

Examination of the world-wide literature reveals that the U. S. concentrated on studies of germanium and silicon while the Soviets concentrated on compound semiconductors.

It appears that a criterion of the present status of the solid-state electrical-device research field is established by the amount and type of research being done on the elements of the fourth column of the atomic table, namely, silicon and germanium, and, secondarily, tin and carbon. Further, it should be noted that it is many times more difficult to arrive at significant fundamental and practical advances through studies of compound semiconductors, such as oxides, sulfides, selenides, and tellurides, than it is to make similar advances using germanium and silicon.

It follows that there is no ill reflection on the quality of Soviet work just because they tackled a much more difficult group of materials than was attacked in the U. S. It should not be construed that low-quality work by the Soviets is the reason why the U. S. is apparently ahead in solid-state electrical-device research. This situation arises because the difficulties encountered in handling compound semiconductors

have tended to retard rapid developments of solid-state electrical devices in the U.S.S.R.

Assuming all other factors to be equal, it is not possible to estimate how much longer it would take to make marked basic and practical advances with compound semiconductors than with germanium and silicon. However, it may be significant that there is evidence that work was started on impurity control, using compound semiconductors, in Germany before 1944 and in the U.S.S.R. before 1946. It is also significant that, with information on germanium available to the English in 1947, they then proceeded to investigate lead telluride, lead sulfide, and lead selenide, and, by 1951, still had not achieved the type of impurity control in the lead compounds that has been achieved in germanium. However, it appears that they are rapidly approaching the point where they will achieve such impurity control.

Several other factors must be considered that modify the above picture. There are no assurances that there was and is so intensive an effort in this field in the U.S.S.R. as in the U. S. It should be recalled that many of the men who are outstanding in solid-state work in the Soviet Union (see list in Section VI) are also outstanding in nuclear physics. A. F. Joffe is an outstanding nuclear physicist. It is known that he went into nuclear-physics work toward the end of World War II (around 1947) and that he is no longer publishing on solid-state work. His last known publication on solid-state work is dated 1946. It is possible that a severe shortage of men to work in the solid-state field developed when intensive atomic-bomb research started in the U.S.S.R.

If it is not assumed that there is a shortage of Soviet solid-state electrical-device research people, it is possible to look at the situation as follows: a large amount of effort behind classified screens may be going on, using germanium, silicon, and other similar semiconductors. It is possible that the information about germanium did not get into the Soviet hands until about 1947. It is also possible that the Soviets did not appreciate, to the fullest extent, the significance of the work that had been done on germanium. As an example, they might have looked at this in the same manner that Europeans looked at Verwey's work on controlled valency in transition-metal oxides. These European scientists, though they did not discredit Verwey, did not accept his viewpoint when he first presented this information. It can probably be construed that the Soviets also adhered to this European philosophy concerning impurities in materials; if so, since the germanium picture is quite similar to that of controlled valency in oxides, it might have been rejected. Consequently, the date at which germanium might have been considered first in Soviet laboratories could have been as late as 1948 or 1949, after the transistor had been announced.

There is another consideration which must be mentioned here, namely, the supply of germanium in East Europe and Asia. There are several conflicting reports concerning this supply. As shown in the Bibliography, there were several articles on the occurrence of germanium and the chemistry of germanium which point to attempts being under way to find this element in the U.S.S.R. Under classified headings, it is known that germanium is of interest to the Soviets in East Germany. Further, it is known that

germanium detectors are appearing in the U.S.S.R. It is possible that the scarcity of germanium has been the prime reason for the lack of Soviet work on this material.

There does not seem to be too much support for definitely stating that germanium work is going on strongly in the Soviet Union and that all of this is being classified. If there is a large amount of work going on in this field, it would be indicative of an amazingly complete classification of selected types of solid-state literature, even to literature on the theory connected with imperfections and impurities in solids which is not present in Soviet literature and which would be a good indicator of classified work on germanium.

Barring the seemingly slim possibility of a perfect Soviet classification system of selected technical literature, it appears that the U.S.S.R. is trailing the U. S. in the solid-state electrical-device research field. This is due primarily to the possibility that they did not study germanium until quite late (assuming they are now) and also possibly to a lack of germanium. Furthermore, it appears from the studies that have been accomplished that a change will have to occur in the U.S.S.R. in order to overcome the advantage in this field which has been obtained by the U. S. as a result of extensive transistor developments.

Attempts were made to determine the rate and extent of interchange of information among people working in solid-state research in the U.S.S.R. A good relative comparison with the situation in the U. S. could not be obtained. This will require a more detailed study than has been possible at this time. Evidence was found of both good and poor industrial -

research institute collaboration. Also, evidence of both segregation and collaboration of research groups was noted. It is worthy of note that many top-ranking men in this field are more than well acquainted with all aspects of the field; this suggests good interchange of information. Definite indications of attempts to improve interchange of information were apparent. The principal instigator along these lines apparently is A. F. Joffe. It is possible that interchange of information among U.S.S.R. scientists in institutes, industry, and various phases of the solid-state research field may be equivalent to that in the U. S.

It could not be determined whether most of the industrial-research personnel are deterred from publishing their work. This could be true because of company policies or government classification, or because industrial researchers are not considered top-ranking personnel. It is to be noted that literature from such sources was in a minority and, in most cases, of inferior quality.

Section II presents a detailed analysis of the various factors involved in arriving at the following conclusions.

Conclusions

1. The Soviets showed an early interest and capability in semiconductor work and were pacing Germany in the field of solid-state electrical-device research in the late 1930's.

2. Soviet work has been directed toward a basic understanding, as well as the practical application, of semiconductors.

3. The Soviets appear to have the potential ability to surpass U. S. efforts in the solid-state electrical-device field. It is not known, however, if they can throw enough manpower and equipment into the field to compete with the extensive developments being made in the U. S. and allied countries.

4. Soviet efforts in the solid-state electrical-device field have been primarily confined to compound semiconductors and insulators, and have involved major studies of (1) luminescence and photoeffects, (2) dielectrics, particularly titanates, and (3) magnetic effects connected with intermetallic compounds and semimetals.

5. The Soviets are trailing in solid-state electrical-device research, apparently because they concentrated their efforts on compound semiconductors instead of elemental semiconductors in 1940 and thereafter.

6. Apparently the U.S.S.R. has only recently started studies of germanium and silicon. It is estimated that this effort is probably not so large and is on a somewhat lower technical level than in the U. S. However, it is important to realize that their efforts on compound semiconductors will prove helpful to them.

7. Examinations of Soviet literature relative to U. S. literature revealed that, with regard to any solid-state electrical device, Soviet versions are either trailing or, at best, only comparable with U. S. analogies.

8. There is suggestive evidence that classification of literature in this field has occurred in the U.S.S.R. since 1949. This is especially true of rectification studies.

9. Evidence of both efficient and inefficient interchange of information among workers in the solid-state research field was found. It is possible that their interchange of information is closely equivalent to that within the U. S.

10. The Soviets have not applied chemical considerations to semiconductor problems so extensively as is necessary. There are indications that they recognize the importance of this.

11. Most of the Soviet leaders in the solid-state research and solid-state electrical-device research fields have been recognized. Exceptions include some of the younger leaders and some in industry or on classified jobs who cannot publish their work.

12. The amount of literature published by Soviet industrial-research men is small and generally of low quality. This suggests that most of the Soviet solid-state research is done by agencies other than industry.

SECTION I

BACKGROUND OF THE SOLID-STATE ELECTRICAL-DEVICE FIELD

1. The Scope of Solid-State Research

In attempting to determine the status of solid-state research in the Soviet Union, it is first necessary to obtain a clear picture of what is meant by solid-state research.

Speaking very broadly, solid-state research is the study of the material world. A specific revelation of the coverage of solid-state research is given in the following.

There are many applied aspects of the solid-state research field, as shown in Figure 1. Here, it will be noted that physics, chemistry, metallurgy, and electrical engineering all have solid-state aspects. The applied fields represented here include all of these aspects.

Figure 2 illustrates, in a schematic fashion, the types of tools used in solid-state research. It will be noted that there are essentially three different kinds of tools: (1) theory which, of course, is important in planning an attack on a problem, (2) experimental tools without which no real information could be obtained, and (3) independent variables (pressure, temperature, and time or frequency).

If solid-state research is viewed from the standpoint of purely basic principles, Figure 3 illustrates the coverage of solid-state research fairly well. It is noted that the total field is divided into five parts, namely, thermal, electrical, mechanical, optical, and magnetic. It is recognized that interactions between parts yield many properties.

In general, it can be said that, if tools selected from those shown in Figure 2 are used for carrying out research in one of the fields shown in Figures 1 or 3, and the studies are conducted on one of the materials shown in Figure 4, solid-state research is being conducted.

At this point, it will be noted that this definition includes both basic and applied research. Also, it will be noted that adequate classification of materials is not given in Figure 4. This figure attempts to classify rigidly all types of solid materials, but it fails to do so since many materials exist as transitions between the types indicated. In addition, it must also be realized that each type of crystalline solid can be either mono- or polycrystalline, and the crystal can be either perfect or imperfect. In passing, it should be emphasized that such small differences as perfection versus imperfection of a crystal means the difference between observing certain types of properties and not observing them. Another comment of import is that one solid chemical species may exist in a variety of states such as vitreous, imperfect crystal, polycrystalline, or perfect crystal.

Although the classification of solids in Figure 5 is not useful in all cases for all purposes, it still is a very simple way of classifying all types of solids, regardless of their crystal structure, perfection, or imperfection of crystals, and whether mono- or polycrystalline. It will be noted that electrical resistivity or electrical conductivity is used as the reference variable in Figure 5. In this classification, it will be noted that metals and alloys, transition materials, semiconductors, and dielectrics are major separations, rather than types of crystals, etc.

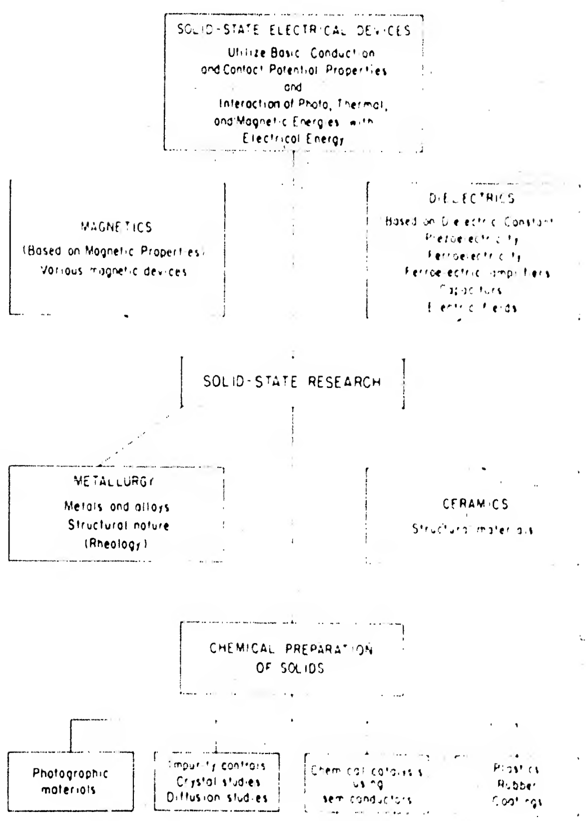

FIGURE 1 FIELDS OF SOLID-STATE RESEARCH FROM THE APPLICATION VIEWPOINT

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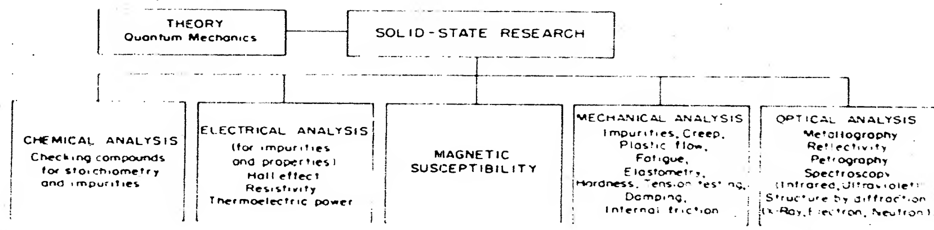

INDEPENDENT VARIABLES

Pressure – high-pressure physics
Temperature – high-temperature physics, cryogenics
Time (Frequency) – pulsing techniques

FIGURE 2 SOME TOOLS OF SOLID-STATE RESEARCH

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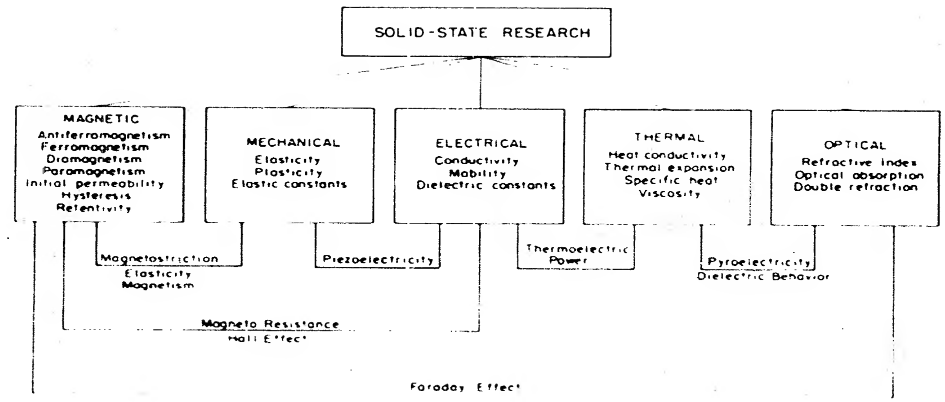

FIGURE 3 FIELDS OF SOLID-STATE RESEARCH FROM A BASIC VIEWPOINT
(Showing properties of solid materials and some examples of the results of interactions between properties)

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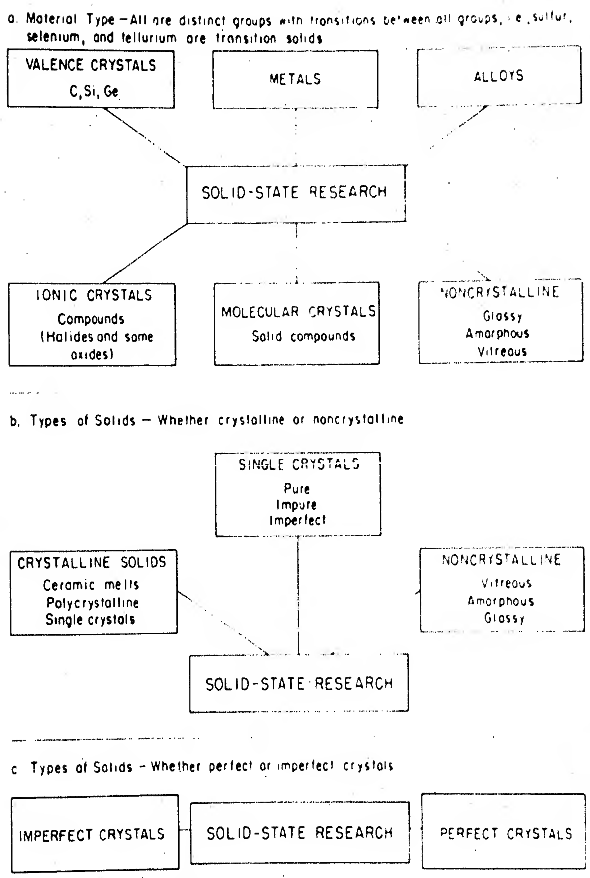

FIGURE 4 SOLID-MATERIAL TYPES CONSIDERED IN SOLID-STATE RESEARCH

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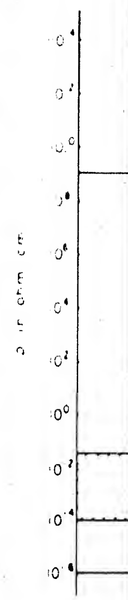

FIGURE 5 CL
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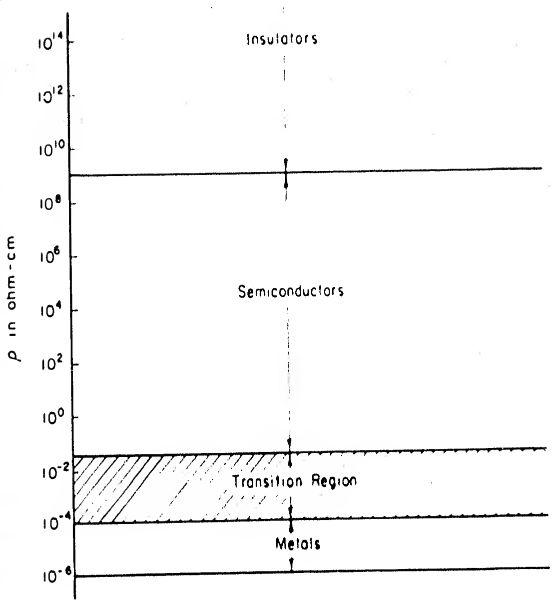

FIGURE 5 CLASSIFICATION OF MATERIALS BY THEIR ELECTRICAL RESISTIVITY

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One very important thing that resistivity as the variable allows, in the consideration of semiconductors, is picturing the variability of one chemical species of material as a function of impurities or imperfections in the lattice. Figure 6 demonstrates this spread for three materials. It will be seen later that resistivity can be helpful in discussing solid-state electrical devices versus nature of material.

a. Factors Pertinent in Selecting Portion of Field to Survey

The preceding discussion has attempted to describe simply and briefly the solid-state research field. It is readily seen from this description that the solid-state research field is both tremendous in size and highly complex. It is quite apparent that some of its aspects are usually considered under other headings, for example, metals. Also, many aspects have both purely scientific and applied practical values. On the basis of this over-all inspection, it was decided that the particular part of solid-state research which should be surveyed would possess three major attributes. These are:

(1) Potentiality to advance the theory of the solid state.
(2) Relationship to the most rapidly developing new industry and to one which is also strongly affecting our way of living, i.e., electronics.
(3) Close relationship to Intelligence objectives of development of electronic guidance and control of new machines of war in aeronautical and associated fields.

The theory of the solid state which is now believed to be applicable for explaining the behavior of all types of solids is based on quantum mechanics, which was developed during the period from 1926 to 1935. This theory postulates that the forces holding solids together have primarily an electrical origin. Quantum mechanics formulates mathematically the forces and motions of each of the atoms in a solid as a function of all the other atoms surrounding it. Expressing the mechanical problem of the motion of a very large number of particles, all exerting large forces on each other, results in a difficult mathematical problem which leads to a stalemate in so far as obtaining a rigorous solution of the equation is concerned. It would take many years to calculate completely the answers to the equation. In shortcutting the stalemate, approximation methods have been used. Theoretical approximations have given quantum mechanical models of the structure of crystalline solids having periodic lattices. The band theory of the solids resulted from such approximation considerations. It must be recognized that it is not the final answer for all cases of the solid state. It should be noted that, since the forces holding a solid together are of electrical origin, studies of the electrical properties of some solids contribute more strongly, rapidly, and directly to the advance of solid-state research than the investigation of any other property.

b. Solid-State Electrical-Device Field

In view of the above, it is possible to select the particular aspects of solid-state research to be surveyed in determining the technical capabilities of the Soviet Union in solid-state research. The ones which

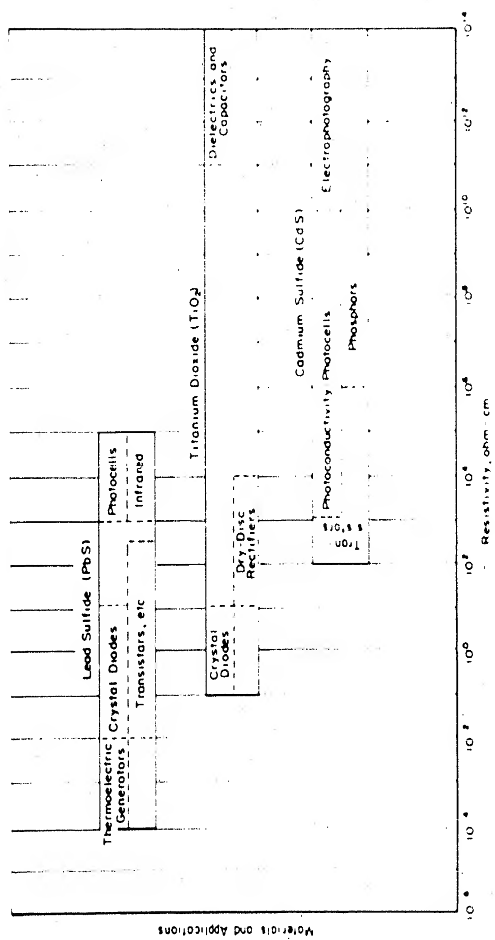

FIGURE 6 ILLUSTRATION OF HOW THE WIDE RESISTIVITY RANGE OF SEMICONDUCTING MATERIALS MAKES ANY ONE MATERIAL USEFUL FOR MANY APPLICATIONS

can be used to describe this restricted portion of the solid-state research field is the solid-state electrical-device field.

A relative picture can be gained of the coverage of solid-state electrical-device research versus the total solid-state research if Figure 1 is reduced to Figure 3. Note that those blocks based on conductivity, dielectric constant, magnetic properties, chemical preparation of solids aimed toward purification of single crystals and control of imperfections, and associated subjects are shown here. The tools of research in Figure 2 are the same, although some are used more than others. From Figure 3, solid-state electrical-device research might be considered as involving the study of electrical, magnetic, and optical segments plus a study of interactions between electrical and all of the other segments shown in this figure.

Figure 4 attempts to describe the basic parts of the solid-state electrical-device field. Here, it is noted that there are essentially three facets to this field, and it should be recognized that this is true, whether the objective of the work is basic or applied. This is a unique feature of this field. A so-called component must often be prepared before fundamental studies can be started. Fundamental studies are not necessarily carried out on the component, but it must be known how the material has to occur in the component in order to conduct pertinent fundamental studies on the material.

In order to help comprehend the extent of this field from all three standpoints, namely, materials, properties, and components, the classification of materials as a function of resistivity, shown in Figure 5,

is of great value. It will be noted there that the resistivity limits at room temperature, within which all materials are found, are 10^{-6} ohm-cm to approximately 10^{18} ohm-cm. Those materials exhibiting resistivities ranging from 10^{-4} ohm-cm to approximately 10^{18} ohm-cm are nonmetallic. In the case of those materials which are nonmetallic, very interesting, variable, and sometimes unpredictable electrical properties are found because their free electron concentration is not so high as in metals. In general, materials falling in this portion of the resistivity spectrum are characterized as follows:

(1) The materials exhibit electrical and associated properties which are related to the resistivities.

(2) Many properties not common to metals are found.

(3) The properties peculiar to these materials lead to many useful applications.

(4) Many of the properties peculiar to these materials are functions of imperfections within the crystals.

(5) The range of imperfectness of a particular crystal may be varied so that its variation in resistivity may be as much as 10^{10} ohm-cm.

Figure 9 illustrates the relationship between the resistivity and the presently known applications of nonmetallic materials. It will be noted that the name of the application, in some cases, also reveals the nature of the particular properties which fundamentally allow the application to be realized. For example:

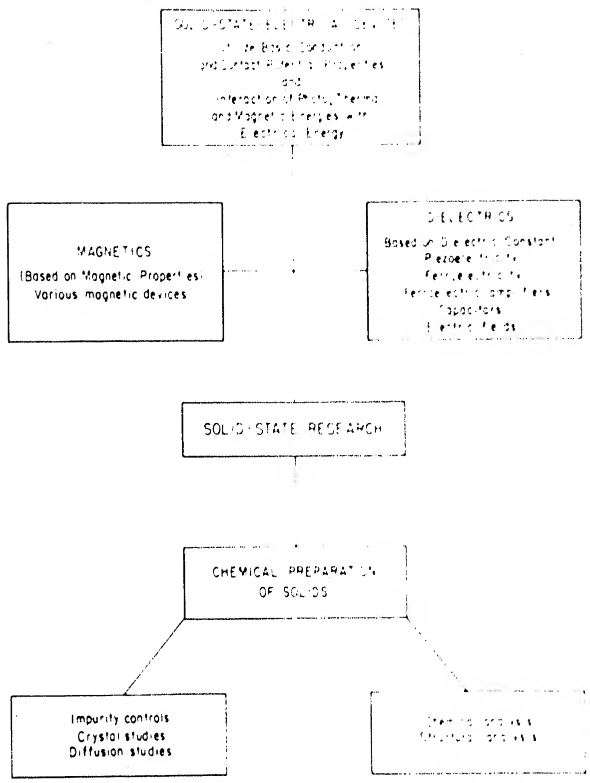

FIGURE 7 SOLID-STATE ELECTRICAL-DEVICE RESEARCH FIELD

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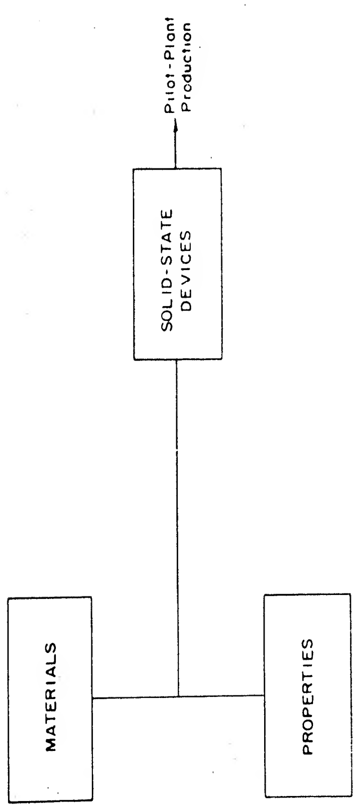

FIGURE 8 MAJOR FACETS OF SOLID-STATE ELECTRICAL-DEVICE RESEARCH FIELD

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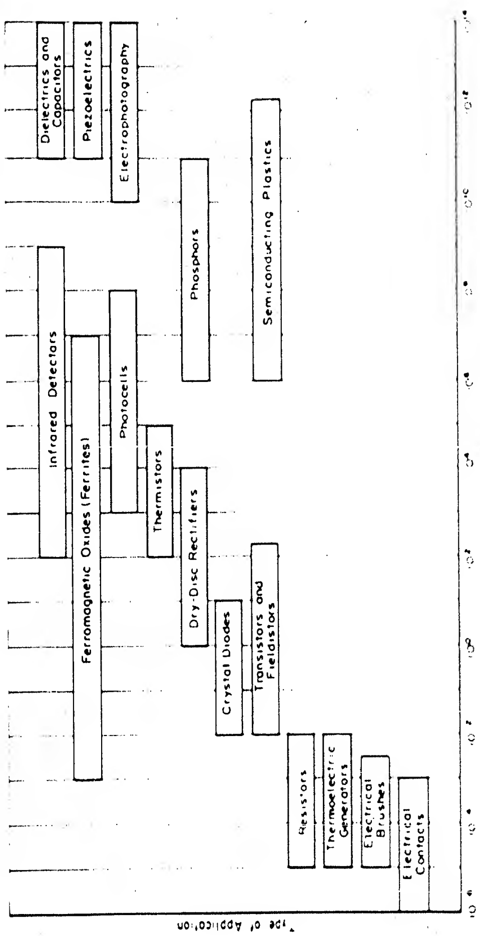

FIGURE 9 APPROXIMATE RESISTIVITY RANGES OF SEMICONDUCTORS AND SOLID MATERIALS FOR SOME APPLICATIONS

(1) Phosphorescence leads to phosphors.

(2) Photoelectric effects lead to photocells.

(3) Rectification effects lead to rectifiers, diodes, and transistors.

(4) Near-zero temperature coefficients of resistance lead to resistors.

(5) Dielectric nature leads to capacitors, electro-mechanical units, etc.

Table I gives some specific information about the general applications indicated in Figure 9. It will be noted that (a) the function of the parts, (b) the nature of the materials used in industry in producing such parts, and (c) some specific offensive and defensive warfare equipment in which these parts are used in the U. S. are given.

Figure 6 shows the range of resistivities exhibited by a few exemplary materials and indicates how shifts of the resistivities in the materials lead to multiple applications of the materials. It is pertinent to point out here that the practical uses of most of these materials designated in Table I cannot be realized until they have been carefully purified, specially treated, and prepared by special methods, which is the function of the materials part of the schematic diagram (Figure 8).

At this point, it becomes possible to describe a little more fully the nature of the blocks in the schematic diagram for solid-state electrical-device research (see Figure 8). In connection with the "materials" block, the work is concerned with purifying materials, "metering" in hyper-purified materials, special impurities, or imperfections which exert a

TABLE I ILLUSTRATION OF COMPONENTS RESULTING FROM TECHNICAL APPLICATIONS OF SEMICONDUCTING AND SOLID MATERIALS

Component	Material Performing Primary Function	Some Applications
1. Dry-disc rectifiers	Se, Ge, Cu_2O, Cu_2S, TiO_2, Si, and Ag_2Se	Power supplies for all types of electronic equipment
2. Crystal diodes	Ge, Si, PbS, TiO_2, and PbSe	Detectors, clippers, limiters, and instruments
3. Transistors, fieldistors, etc.	Ge, Si, PbS, and PbSe	Amplifiers and bistable elements for computers
4. Thermocouples and thermoelectric generators	PbS, ZnSb, and PbTe	Temperature detectors and thermal generation of power
5. Resistors	Carbon, borocarbon, Pd-Au alloys, nitrides, silicides, and oxides	All electronic applications, type depending on application conditions
6. Thermistors	LiO, NiO, Ni-Fe-Co oxides, and In_2S_3	Temperature detection and temperature controls
7. Varistors	SiC, rectifier materials, and $BaTiO_3$	Lightning arrestors and voltage variable-resistance controls
8. Phosphors	Silicates, phosphates, sulfides (CdS, ZnS), and halides	Markings, visual display of information from radar, electroluminescent plates, etc.
9. Photocells	Se, Cu_2O, Tl_2S_3, PbS, PbSe, and PbTe	Light-sensing devices and control by use of light
10. Infrared detectors	PbS, PbTe, and PbSe	Detection of infrared

TABLE I (Continued)

Component	Material Performing Primary Function	Some Applications
11. Magnets	Ferrites (ferromagnetic oxides), Fe, Ni, Zn, Mn, Li oxides	High-frequency transformer cores, tuning slugs, and antenna rods
12. Electrical brushes	Graphite and metal-graphite combinations (possibly MoSi, InS)	Commutation and electrical contact to moving, movable members
13. Electrical contacts	Metals, alloys, etc.	All electronic applications
14. Piezoelectric elements	$BaTiO_3$, quartz, and Rochelle salt	Pressure-sensing devices, electro-mechanical transducers, and frequency control
15. Dielectrics and capacitors	$BaTiO_3$, TiO_2, mica, paper, plastics, glass, etc.	All electronic applications
16. Electrophotography	Se, ZnS, CdS, and Se-Te eutectic	Rapid, dry copying of maps, printed matter, and X-ray detection
17. Semiconducting plastics	Carbon-impregnated organics	Instrumentation and shielding
18. Crystal counters	Diamond, ZnS, CdS, and anthracene	Controls, thickness measurement, monitoring, and detection
19. Semiconducting glazes	Special ceramics loaded with Fe_2O_3	Heater resistors, heating, and cleaning high-voltage insulators
20. Transparent conductors	SnO_2, In_2O_3, and CdO film in glass	Heating windshields, electroluminescent plates, resistors, etc.

definite control on the electrical characteristics of the semiconductor, and developing methods of producing quantities of this material in the same electrical and chemical states.

The block labeled "properties", on the other hand, may be considered as follows: In this category are all the basic evaluations of the properties of materials produced that can be classified as electrical analyses. Work aimed at arriving at electrical calibrations which indicate the degree of purity or the degree to which control is achieved in metering in one impurity, etc., is included. In the case of dielectrics, the nature of the investigations is somewhat different. However, in all cases, useful components as end results can be achieved only if both the materials and the properties aspects are thoroughly considered.

c. A Yardstick for Evaluating Progress in Solid-State Electrical-Device Research

In attempting to measure the technical capability of a country in solid-state electrical-device research, it is obvious that the number of people, the laboratories, and also the general type of equipment available must be considered. Of great importance, however, is the type of organization set up to handle the field. It is of greatest importance that the organization involve three parts, i.e., materials, analysis of properties, and component development, as is indicated in Figure [illegible]. It would appear that the Soviet capability in the solid-state electrical-device field would be measured by their ability to make and control crystalline materials, specifically in regard to types, amounts, and dispersion of impurities and

imperfections; the extensiveness of their evaluation of the electrical properties of these materials; the demands of their electronics industry; and the ingenuity used in developing solid-state devices.

2. World-Wide History of Solid-State Electrical-Device Research

Solid-state electrical-device research is a hybrid field. Prior to 1934, this field did not exist. In general, to start this field fully, it required (1) the development of quantum mechanics, (2) the growth of the electronics industry, and (3) the recognition that numerous materials exhibit many of their electrical and optical properties only because they contain imperfect crystals.

Solid-state electrical-device research assumes a rather unique position. It is a field containing primary mysteries which are functions of impurities and imperfections in lattice structures. However, the same specimens which are being studied to obtain new knowledge simultaneously are being considered for production, since the specimen must often be in the form of an electrical device before it can be studied basically. It is this fact that makes it necessary for any organization doing this type of research to have the facilities for doing applied research, as well as fundamental research. Actually, selenium and copper oxide rectifiers, carbon resistors, and a few other solid-state electronic devices came into existence before the solid-state electrical-device field had its stabilized beginnings. These devices were items made by recipes and were used to some extent in the electrical industry in the early period before 1934.

Outstanding milestones in the early development of the solid-state electrical-device field include the following:

(1) About 1934, the quantum mechanical theory was completed. This theory can explain the behavior of solids. Subsequently, Wigner in Germany, Slater in the U. S., Mott in England, and A. F. Joffe in the U.S.S.R. set up schools for the purpose of applying this theory to solids. The first important result obtained was the solution to the quantum mechanical equations for solids using approximation methods. This resulted in the band theory of solids, which is a fundamental cornerstone of solid-state electrical-device research.

(2) About 1937, both Schottky in Germany and Davydov in the U.S.S.R. developed barrier-layer space-charge theories to explain selenium rectifiers. These theories and the assumptions contained in them were based on the band theory of solids and formed another basic cornerstone of this field.

(3) The electronics field had steadily developed all over the world from about 1905. During the 1930's, this field was ready to take a significant place in the world. Political and associated events of the late 30's were all that was necessary to initiate the rapid growth of the electronics industry. The demands for new, more powerful, higher frequency, more reliable, lower cost, smaller, etc., electrical devices became evident in the early 40's.

(4) Basic studies of the properties of solids indicated that many properties could not be accounted for on the basis of the band theory of solids, which is based on the assumption of a perfect lattice structure.

The semiconducting materials were examples of materials with unexplainable properties. Consequently, studies were started in the late 1930's on selenium and copper oxide and other semiconducting materials in order to arrive at some explanation of the variable conduction in them and, subsequently, to exploit them further in devices other than rectifiers.

Meshing these events together spells out the solid-state electrical-device field. A bird's-eye view of the major activities accomplished in the late 1930's and early 1940's is obtained in the following way:

For some idea of how the solid-state electrical-device research field shaped up in various parts of the world as a result of these beginnings in the late 1930's, it is worth while to examine several pieces of literature. Consideration of an article written by N. S. Sominsky(1), an excerpt from a research planning program written at Osram Company(2), Germany, and the general status of work on semiconductors and solid-state electrical devices in the U. S. around 1940 leads to the conclusions discussed below.

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(1) The Leningrad Physico-Technical Institute of the Academy of Sciences, U.S.S.R., N. S. Sominsky, J. Exptl. Theoret. Phys., U.S.S.R., May, 1940, Vol 10, pp 576-580.

(2) Excerpt from a planning program entitled General Program Suggested for Application of Semiconductors Based on Scientific Considerations, Osram Company, Germany, 1944-1945.

Translations of (1) and (2) are included in Appendix I.

The German work outline for the field of semiconductors and allied fields is primarily a group of suggestions concerning the invention of new, practical, solid-state electrical devices. Examining this work outline from the vantage point of the present, and looking back to the state of the semiconductor field in 1945, results in an amazing conclusion, namely, that much of the work accomplished during the past six years in the U. S. is predicted by this outline. New developments, such as transistors, electroluminescent plates, thermistors, new catalysis methods for solid-state studies, new rectifiers, both dry-disc and diode types, electrostatic clutches, high-temperature rectifiers, semiconductor cathodes, new infrared photocells, and low-noise-level and low-temperature-coefficient high-stability resistors were predicted or indicated as development possibilities in this outline.

Several repercussions of this revelation are to be noted. First, the Osram Company was located in Berlin, and it was almost totally encompassed by the Soviets in 1945. The plants of the Osram Company were confiscated and removed to the U.S.S.R., and many of the personnel were taken to the U.S.S.R. It is expected that the Soviets, therefore, obtained the advantage of this same outline. Another type of repercussion, however, is the implication of this outline as to the extent of semiconductor and solid-state electrical-device research in Germany during the period between about 1938 and 1944. In order for this outline to have been written, extensive studies must have been made in all of these fields.

From information obtained during a trip to England, where many Germans attended the International Semiconductor Meeting in 1950, it was

discovered that the huge amount of work done during this period was confined to compounds. Apparently, no work had been done on germanium or silicon in Germany.

Sominsky's article conveys the impression that the Soviets were considering solid-state electrical-device research in an excellent fashion, having a laboratory devoted to it and an organization set up which could function along fundamental and applied lines. This article also conveys the idea that only compound semiconductors were investigated.

Two other articles, one by Oster(1) and the other by Luk'yanov(2), are also helpful in evaluating the status of Soviet solid-state electrical-device research during the infancy period in the late 1930's. They give some idea of its electronics background. These articles tend to support the opinion that research in the Soviet Union in the decade of the 1930's achieved just as high standards as electrical research which was carried on in Germany and the U. S.

Actually, the beginnings of solid-state electrical-device research, inclusive of the type of organization required for doing this research, were not effective in the U. S. until about 1941, somewhat later than in other countries. At least this is the impression obtained from the open literature. It is known, however, that considerable effort was in progress before 1941 at various laboratories, such as the Bell Telephone

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(1) Electrical Research in the U.S.S.R., Gerald Oster, J. Appl. Phys., March, 1945, Vol 16, pp 121-124.
(2) Thirty Years of Soviet Electronics, S. Yu. Luk'yanov, Uspekhi Fizicheskikh Nauk, 1947, Vol 33. A translation is included in appendix 1.

Laboratories and General Electric. This type of research with it's required organization started in 1941, on the eve of U. S. entry into World War II. Germanium and silicon were the materials chosen, and the purpose of the work was primarily to develop radar, namely, first and second detector diodes in radar and ultrahigh-frequency communication units.

In general, when the infancy period of solid-state electrical-device research is scrutinized, it is evident that, in the U.S.S.R. and Germany, the required moves for developing this field were made earlier than in the U. S., thus giving them a time advantage.

SECTION II

ANALYSES LEADING TO ESTIMATE OF RELATIVE STATUS OF SOLID-STATE RESEARCH IN THE U.S.S.R. AND THE U.S.

In this Section, information is presented which attempts to show the reasoning used to arrive at the statements and conclusions presented in the Discussion of the Summary portion of this report.

1. Over-All Analyses

Grouping of the literature on solid-state electrical devices and research into the outline of semiconductor materials and associated work, as used for the World-Wide Digest of Literature on Semiconductors in 1950 and 1951, has been shown to be effective in demonstrating those portions of this field which are of major interest to the Soviets. The personalities, fields of interest, and facilities of interest, as established from the literature survey, all agree quite well with those indicated by other investigators. These results suggest that the sampling of the literature was adequate. However, the validity of any conclusions made must be based on an estimate of how good a sampling of Soviet literature was obtained and whether the Soviets have done work under secrecy. It is to be emphasized that only the overt literature has been used for this study.

2. Literature Considerations

a. Journals

A list of 1[illegible] journals is given in Section III. It is thought that a continuous scanning of work being published in the solid-state [illegible]

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field would be possible by procuring the nine journals presently being published. Since procuring this many journals might be a problem, a good estimate could be made by looking at the journals from which more than 50 per cent of the data for the subject study were taken. These are:

(1) Doklady Akademii Nauk, S.S.S.R.

(2) Journal of Technical Physics, U.S.S.R.

(3) Journal of Experimental and Theoretical Physics, U.S.S.R.

(4) Journal of Physical Chemistry, U.S.S.R.

This reasoning assumes that the journals will continue publication along the present lines. However, even deviations in publication procedure might be indicative of political or military attitudes toward either whole fields of endeavor or certain applications.

b. Coverage of the Literature

From inspection of the literature, it appears that the Soviets have directed their activities in the solid-state electrical-device field over a broad region. By putting the literature into a form such as Table V in Section IV, it is possible to point up the fields of major interest to the Soviets.

Their extensive work in theory and electrical properties, particularly over a wide range of semiconducting and associated materials, indicates a good foundation in semiconductor research and application. Their major interests in the application of semiconductors seem to be (1) luminescence and photoeffects over a wide range of excitation frequencies, (2) dielectrics, particularly titanates, (3) rectifiers of all types, and (4) magnetic effects in intermetallic compounds and semimetals.

The complete lack of Soviet publication on germanium is probably not due to a lack of interest. In view of the great amount of data available today on germanium and its attractive applications, it seems unlikely that the Soviets are not interested. Undoubtedly, germanium is in short supply in the U.S.S.R., but certainly there is enough available to them for considerable work to be done. Only small amounts are needed for components such as diodes and transistors. Their work on silicon (classified) since the war years also belies the fact that they are not capable of or interested in working on crystal devices.

c. Quality of the Literature

The translation and evaluation of several items of literature in various fields, discussed in Section IV, has shown that the quality of Soviet work in the fields in which they have been active is generally very good. It has been recognized by many investigators that the Soviet ability in the theoretical aspect of the solid-state field is excellent.

From the theoretical aspect, Shifrin's work in 1944 on impurity of metals is commendable. Actually, in this work, Shifrin was considerably ahead of the rest of the theorists in the world, but apparently the Soviets were not able to solve their impurity problems so quickly and completely as did the U. S. In 1946, A. F. Joffe and others were bordering closely on the field of transistor effects, which they apparently missed. The "polaron" theory of Pekar is also highly commendable.

The Soviet application of semiconductor developments has apparently been good. In this field of application, planning plays an important

role. Some examples of good planning on their part are (1) the high-temperature alloys used in their jet engines and their thorough and excellent studies of metals, (2) the work leading to barium titanate production and application, (3) development of the 6,000 - 10,000 microampere/lumen thallium sulfide photocell, (4) the high-voltage selenium rectifier announced in the early 1940's, and (5) the emphasis on radiation receivers and, in general, the application of optics to military science. Their system of distributing developments to industry may be very good and is shorter in route than it is in the U. S., since patents are of no concern and the State is all-powerful.

d. Literature Statistics

The study shown in Table V of Section IV points out that the publications of the more recent years (1949-1951) are probably the least reliable for drawing conclusions on the basis of overt literature. This is unfortunate in that the recent years are those of greatest interest. Apparently the Soviet stoppage of publications leaving the U.S.S.R. has provided in part the censorship desired.

It was found that about 7 per cent of the literature in the Digest of Literature on Semiconductors for both 1950 and 1951 was of Soviet origin. From 1950 to 1951, there was an increase in the number of publications in some categories, as is shown by Table II.

In scanning several works accomplished in the U. S., Germany, and England, which had large bibliographies, it was noted that very few of the total number of references were Soviet. In scanning a large number of

TABLE II BREAKDOWN OF SOVIET LITERATURE APPEARING IN THE DIGEST OF LITERATURE ON SEMICONDUCTORS FOR 1950 AND 1951

Category Into Which Reference Falls	1950	1951
Solids in General	8	15
4th Group Elements	1 (on carbon)	2 (one on carbon; one on tin)
6th Group Elements	1 (on selenium)	1 (on selenium)
Compounds		
Oxides	1 (on copper-aluminum)	8 (one on zinc-cadmium; three on copper-titanium; four on others)
Sulfides, Selenides, and Tellurides	6 (one on cadmium sulfide; one on zinc sulfide; four on others)	4 (one on cadmium sulfide; two on lead sulfide; one on others)
Halides	2	2
	9 Subtotal for compounds	14 Subtotal for compounds
Other Materials	1	1
Total for Year	20	33
Percentage of World Publications	7.27	7.3

Soviet articles, the bibliographies generally contained a number of German references and very few English references. It is only natural for an author to refer to works which are most familiar to him, and these would probably be in his own language, except for the ones outstanding enough to be translated.

With the idea that most of the foreign references would be those considered important or outstanding, the book by Quill* was used as a test case. Semiconducting materials, such as sulfides, selenides, silicides, and phosphides, are considered in this book. The number of Soviet versus the number of English, U. S., Dutch, German, etc., references was recorded. It was noted that Soviet references predominated for the sulfides, selenides, silicides, and phosphides. This agrees with the data in this study which indicate that the Soviets are strong in the field of compound semiconductors. The test also indicated that this method of detecting outstanding fields of the Soviets may be useful.

3. Influence of Germanium on the Solid-State Field

a. General Considerations

The specific influence of germanium developments on all of solid-state research must be recognized before there can be an appreciation of the effect on the U.S.S.R. status in solid-state electrical-device research which has resulted from either their failure or delay in investigating germanium. It must also be realized that work on silicon and germanium in

*The Chemistry and Metallurgy of Miscellaneous Materials; Thermodynamics, L. L. Quill, McGraw-Hill Book Company, Inc., New York, New York, 1950, 329 pages.

the U. S. has had a startling effect on the vacuum-tube amplifier, photo-element, thermoelectric-generator, resistor, and dielectrics fields. In fact, full understanding of the electrical properties of all solids has been advanced by germanium studies. The reason for this is that the germanium crystal lattice is simple since the lattice involves only one element and the bonding of all the atoms is achieved by one type of bonding force, the homopolar bond. The following listing illustrates how the study of germanium has contributed to an understanding of solids:

(1) An understanding of impurity scattering and lattice scattering on electrical conductivity is a basic consideration which led to (a) the bombardment of germanium in neutron irradiators in the interest of studying radiation-damage effects, (b) using electrical methods for detectors, (c) the explanation of the mechanism of conduction in germanium and silicon, and (d) a new insight into possible factors influencing conduction in compound semiconductors.

(2) Additional information on crystal habits was obtained from a study of low-temperature properties. Germanium, being a semiconductor, is expected on the basis of simple theory to have infinite resistance at absolute zero, thus making it easy to recognize if simple theory is adequate. This is in contrast to metals, which exhibit the lowest resistances at absolute zero.

(3) A better understanding of contact potential, surface mobility, and space-charge barriers has been gained.

(4) The concept of potential barriers within single crystals as a definite demarcation line between regions containing two different types

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of impurities forms the basis for a new field of electrical circuits in crystals. The partially proven concept of "positive holes" was strongly verified through work on germanium.

(5) It was because of the anomalous contact-noise and contact-potential characteristics noted at contacts between metals and germanium that the theory of surface states was developed and, subsequently, the transistor was achieved using germanium.

(6) One of the first examples of the case of electron waves interacting with acoustical modes was found. (It should be noted that the Soviets' Polaron Theory also considers this type of interaction.)

(7) Theories of impurity positions in the germanium lattice tended to substantiate Verwey's argument concerning the controlled-valency theory for the transition-metal oxides. The Verwey theory had been somewhat poorly accepted in Europe prior to this time.

(8) There have been repercussions from the barrier-layer theory and proving out of the concept of interior P-N junctions in germanium crystals in connection with the breakdown theory of dielectrics.

(9) Without the prior germanium activity, work on lead sulfide, lead selenide, and lead telluride, now going on, might not have progressed so rapidly. Here, purification is partly accomplished by growing single crystals, and identification of purity of the crystals is achieved through measurements of electrical properties.

(10) The degree to which the band theory of solids has been checked as a result of germanium work is quite significant, and deserves the highest praise.

It can be said that the present experimental approach to phosphors, electroluminescence, photoemission, and photoconduction has been influenced by germanium work. The barrier concept of photoconduction has come about as a result of these findings and of the atmosphere created by germanium studies. Realization that chemical catalysis is directly related to impurity semiconduction through the effects of impurities on electrochemical potential was the result of germanium findings. Today, there is an immense influence of ideas and concepts stemming from germanium studies on the whole solid-state field. Applications are being made to silicon carbide, lead compounds, selenium, copper oxide, and cadmium sulfide, to mention a few examples.

b. Evidence Suggesting That Germanium has Not Been Considered in the U.S.S.R.

Measurement of the impurity concentration in semiconductors using the resistivity and the Hall constant versus temperature actually was accomplished in the case of germanium. This has not yet been accomplished in the case of compounds, but there is some hope now in view of what has been done in the case of germanium. The case of compounds is very complicated, and it is noted in the Soviet literature that attempts have been made to do the type of job in this field that has been done on germanium in the U. S.

The lack of achievement of impurity control by the Soviets is not too unexpected considering the materials on which the Soviets chose to work, namely, compound semiconductors. It has only been recently in England that some success has been obtained in bringing lead telluride,

lead selenide, and lead sulfide under control, i.e., with regard to purification and subsequent control of their electrical characteristics. Even here, additions of selected impurities to obtain selected electrical characteristics are still not completely investigated. In other words, the difficulties confronted in such compounds are tremendous. There are all types of disagreements, as well as all types of variables, which are difficult to control. The chemist and the physicist do not quite agree when looking at these compounds.

Although there were definite suggestions by A. F. Joffe in 1946 that they were cognizant of the need of impurity control in the case of semiconductors, no other literature article particularly describes achievement of this impurity control. There is nothing in the Soviet literature on either Rutherford or lattice scatterings in solids, such as permeates the U. S. literature now. This is very important in understanding the properties of semiconductors.

If one does not consider that nuclear physics had any effect on the solid-state electrical-device work in the U.S.S.R. and one looks at the various trends in the occurrence of literature as a function of time from 1940 to 1950, it will be noted that there was a drop-off in the rectifier literature about 1947. This was coincident with the extensive publications on germanium diodes and transistors in the U. S., namely, about 1947 and 1948. It might be construed from this that the Soviets who were working on selenium were transferred to considerations of germanium. If this was the case, and considering the period of time, the amount of money and manpower required to develop germanium in the U. S., and the type of literature which

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was available to the Soviets up to 1947, it could not be expected that good transistors, especially junction transistors, phototransistors, etc., would become available in the U.S.S.R. before 1951. It must be recalled that techniques for treating germanium were not publicly available in the U. S. much before 1950.

c. Reasons Why the U.S.S.R. May Not Have Considered Germanium Until Recently

The Soviets had no opportunity to obtain information on germanium, since the work which started in the U. S. was kept from the published literature from 1942 to 1946. All information on transistor investigations was kept secret until 1948. Therefore, the Soviets may not have realized the importance of germanium until about 1947 or 1948, probably as a result of several circumstances, such as the following:

(1) The work load on a few Soviet people, who were already working in worth-while fields of activity, was so large that they did not have time to consider other fields.

(2) The nonavailability of germanium.

(3) The conflict of chemical and physical thoughts concerning impurities in semiconductors.

(4) The status of the world's understanding of the solid state in the early 1940's when the Soviets, along with Germany, were leading the solid-state field.

(5) The pressure of German methods and German attitudes in solid-state work.

Fortunately for the Soviets, the lack of experimental evidence to support the qualitative data that they had already uncovered was leading them in the right direction, i.e., they were heading toward the barrier concept of the solid state. This is strongly indicated in the case of P-N junctions in single crystals of germanium. Again, it is noted that the right approach was made but in the wrong direction. The rigid control by their leaders, with respect to certain decisions which they could make concerning the direction in which research was directed, and also the German influence in the U.S.S.R., which did not accept the Verwey type of concept of impurities in solids, all probably tended to make the Soviets miss the germanium picture.

It would appear that the Soviets entered the germanium field later than did the U. S., <u>if</u> they have entered it. There is fairly good evidence that they have started work on germanium, as indicated by the use of germanium in East Germany and the finding of germanium detectors in some of the civilian radio sets in the U.S.S.R. Evidence of the following types seems to indicate that the tremendous research potentiality that they have may now be active in the fields of germanium and silicon:

(1) The drop-off in their excellent rectifier literature about 1947. The transistor was announced in early 1948.

(2) The work plans at the Physico-Technical Institute, as stated by A. F. Joffe in 1941 and 1946.

(3) Literature of a purely chemical nature on extraction of germanium from ores, etc.

(4) Soviet confiscation of German companies and technicians (such as the Osram Company) could not help but make available to them the excellent German technology along these lines.

4. Relative Status of the U. S. and the U.S.S.R.

It is apparent from the Digests of Literature on Semiconductors for 1950 and 1951 that great strides have been made on the problem of controlling semiconductors, and impurities and imperfections in them. Also, progress has been made in understanding the reasons for their electrical properties and how to modify them, including how to set up particular geometries of electrical space charge within single crystals. This is a wonderful advance and the very heart of what is necessary for realizing reproducibility and, therefore, application of semiconductors. It should also be recognized that this is absolutely necessary for fundamental advances. The great success of the U. S. in this field is a direct result of the tremendous growth of the electronics industry during the years 1940 to 1950 and the evolution of a very large number of groups of teams working on semiconductors throughout the nation. These conditions were not present in 1940. Also, in the U. S., close control of the research programs has not been maintained. This was an advantage during the early stages of the development of the solid-state field, in the late 1930's and early 1940's, since many lucky experimental accidents occurred without extensive theoretical consideration for carrying out the experiments.

The situation of the Soviet Union in 1940 in regard to organization and the subjects being considered was ideal for extensive applications

in the field of semiconductor devices. In 1946, evidence was given by A. F. Joffe that substantial gains had been made in the right direction. The question is asked then, why, in 1952, evidence was not present, in the Soviet open literature, of the many developments which naturally would come from further progress in this field. There are several ways to look at this:

(1) The amount of effort put into the investigations in the U. S. was tremendously greater than that exerted in the U.S.S.R. from 1946 on. This is particularly true because of the free-enterprise system and U. S. industry's recognition that the transistor has many possibilities.

(2) The number of scientific people in the U.S.S.R. was insufficient for putting a large effort into nuclear-physics research and solid-state electrical-device research simultaneously, so the wonderful program started in 1940 and continuing through 1946 may have been sacrificed for intensive efforts in the field of nuclear physics. This is suggested by the transfer of well-known solid-state research men, such as A. F. Joffe, into the nuclear-physics field in about 1947.

It is not that the Soviets are incapable of doing the work required for germanium studies, but only that there may have been resistance to doing it. This is based on the well-justified and tremendous complications that they naturally encountered in dealing with the compound semiconductors which they had selected as the materials to explore very thoroughly. This placed them on a basic path, but an experimentally difficult one, which they so far have failed to conquer due to a number of reasons. One might have been their unwillingness to accept new approaches, such as perhaps

Verwey's approach in the case of transition-metal oxides. The ultimately desirable relationship of materials, properties, analyses, and development work was present in the U.S.S.R. earlier than elsewhere. This, however, worked to their disadvantage because of the gap between physics and chemistry which is only now being bridged through the consideration of imperfections and impurities in the case of semiconductors.

The relative trends which seem to be present in solid-state research are as follows: In 1940, it appeared that the Soviets were somewhat in advance of the U. S. and were pacing the Germans so far as investigation of semiconductors was concerned. They were going ahead toward an ultimate goal in solid-state research, namely, determining the behavior of solids and the effects of anything that could change the properties of solids. However, in 1950, because imperfections and impurities mean so much to the properties of solids, and the control of them means ever more in obtaining applications of those solids (especially the semiconductors and dielectrics), it was apparent that the U. S. was the leader, with The Netherlands, under Verwey, not far behind. There is now intensive effort going on in Germany and England for the purpose of catching up in the germanium field. Here, the U. S. tends to rank first, as evidenced by the discovery of the germanium diode, the transistor, the phototransistor, etc.

The very nature of this picture suggests that the tremendous weight of early information in the field of solid-state research may help the Soviets at this time in overcoming the advantage that has been obtained by the U. S. through the intensive investigation of germanium in this country. Science is such that, with the advantages

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the Soviets have had since 1945, they could forge beyond the U. S. in the solid-state field. They were stymied by being on too difficult a road, and this, along with the Government's favoring of nuclear work, is the only reason which can be given at this point as to why they apparently are not working on germanium.

It also follows that they are now probably applying tremendous effort to work on germanium and silicon, but are keeping the results behind classified screens. In view of their attitude toward publication of those data which they have developed first, it is evident that they would be publishing on germanium and silicon if they were in a position to do so. It can be more or less predicted that, in the next year or so, unless they keep this information completely classified, they will be publishing on germanium and silicon. All of the various evidence evaluated from every standpoint suggest this.

In view of the tremendous advances in understanding the solid state (which are centered in germanium and silicon development) and their strong influence on the material development which is the heart of solid-state research and without which the current progress in solid-state fields would be impossible, several points can be made:

(1) The lead that the U. S. has today is substantial.

(2) The Soviets are probably now on the "beaten path" of studying germanium and are applying all the effort that they can muster.

(3) In the next few years, their work on germanium will affect all of their other researches in the solid-state field, since the new insight into impurity control over usable properties is applicable, with a few limitations, to all solid-state research.

(4) The Soviet research organization, as indicated by the literature of the early 1940's, is suitable for immediate and effective consideration of germanium and silicon.

(5) In their work on compounds, the Soviets have surrounded the area of germanium and silicon without actually investigating it. Now that they are probably studying this field, their knowledge of the surrounding area will have a pronounced effect on the rapidity of the development.

5. Soviet Facilities - Their Staff and Equipment

The method of collection of open literature did not lead to extensive data on the location of facilities. It is thought that the covert literature and "survey"-type articles may be useful toward this end. For example, the abstract of the Seventh All-Union Conference on Semiconductors, held in 1950, gives some insight into the Soviet laboratory organization.

There appear to be several facilities which are of prime interest to the field of electrical devices and semiconductors. These are:

(1) Leningrad Physico-Technical Institute
(2) Institute for Physical Problems - Moscow
(3) Physics Institute imeni P. N. Lebedev - Moscow

(4) Mathematics Institute imeni V. A. Sekolov

(5) Institute of Crystallography - Moscow

The first three of the facilities listed are well-known centers of semiconductor work. The last two are facilities which do associated work pertinent to the field of semiconductors. Undoubtedly, there are others which should be added to this list.

During the Semiconductor Conference in Reading, England, in 1950, a telegram was received from Vavilov in Leningrad, pointing out that the Soviets were sorry that they could not attend. This indicates that the center of solid-state and semiconductor work is located in Leningrad. The aforementioned Seventh All-Union Conference on Semiconductors also supports this idea.

In considering facilities, the personalities with whom they are staffed are also of interest. The specialties of the personalities can also give a good indication of what type of activity is going on at the facility. In Section VI, personalities are listed in various ways, namely, (1) an alphabetical listing, (2) by fields or specialty, and (3) outstanding personalities by their fields of interest. This listing is thought to be rather complete and particularly useful as a "watch list" in the case of less well-known personalities. It is to be noted that the outstanding personalities listed are not exactly those whom other investigators have listed. Generally, the listing given in this study will be the broadest because (1) fringe fields, such as crystallography, have been considered, (2) some lesser well-known personalities have been included in the interest of their future work, and (3) the field of solid-state electrical-device

research as defined in this study is quite encompassing. The list would naturally change gradually as the years go by.

Because of the broad scope of work in the solid-state physics field, it is not possible to say much regarding the scientific equipment which might be available to the Soviets. The tremendous amount of confiscated German equipment, for example, from the Osram and Zeiss Companies, should add substantially to what apparently were well-equipped laboratories. The excellence and nature of their fundamental studies suggest that they are well equipped with the necessary tools. It must be pointed out that the apparently well-equipped condition of the laboratories, such as is the case at the Leningrad Physico-Technical Institute, does not necessarily indicate that there is sufficient scientific equipment available for production use and quality control.

6. Discussion

It is thought that this study can be considered as a basis upon which further analyses can be built. It has definitely been shown that the overt literature can be an important phase of Intelligence studies in the solid-state-physics field. The Soviets' major fields of interest, facilities, and outstanding personalities pointed out by this study all seem to agree quite well with those indicated by other investigators.

If information from the covert literature is integrated into a similar study, it seems that a continuous scanning of the Soviets' activities in this field would be possible. With their background knowledge of compound semiconductors, they could make extremely rapid progress in the

germanium-silicon field. Since germanium work is the key to progress at the present time, it would be well to know all of the Soviets' activities along these lines.

Another factor which must be taken into account is that Soviet classification of certain large areas of literature could void some of the conclusions drawn in this report. This is particularly true in the case of germanium and silicon work. However, it seems unlikely that such an extensive classification program would be possible. It would be well to establish, if possible, what the Soviet attitudes toward classification of solid-state electrical-device research might be.

SECTION III

COLLECTED SOVIET LITERATURE IN THE SOLID-STATE ELECTRICAL-DEVICE FIELD

1. Introduction

This section describes the Bibliography of all the collected Soviet literature in the solid-state electrical-device field and associated fringe fields, with justifications for the period of time considered.

There were several facts which were considered in determining the period of time for which the literature should be investigated. These facts are as follows:

(1) Although some parts of the solid-state electrical-device field have beginnings before 1936, the actual beginning of the field was about 1938. Therefore, it would be of no use to investigate any period prior to 1935-1938.

(2) The period of time from 1939 through 1951 has included the largest growth of the electrical industry. (Relatively speaking, this industry has had a larger growth than any other industry during the same period.) In view of the applied aspects of the solid-state electrical-device research field, particularly in the electronics industry, it would be expected that this period of time would include the greatest effort and thus be of greatest interest.

(3) Probably of greatest importance in determining the time period are the political events which occurred from 1938 to 1952. It is apparent that from 1946 to 1952 (the cold-war years), the latter two or

three years represented the period of poorest collaboration. The period from 1940 to 1946 was the time of collaboration. The period around 1940 and earlier could be labeled as a period of somewhat disinterested relationships. Consideration of these political trends suggested that the Soviet open literature probably would have been affected during the years of poor or poorest collaboration. In addition, it was recognized that the latter part of the period up through 1945 would be deficient in literature, owing to the pressure of war. Consequently, it was concluded that the period from 1940 to 1951 would have to be covered to make an evaluation of Soviet capability in the solid-state electrical-device field.

2. Journals of Interest

The Bibliography which was the basis of this study, was compiled from a total of 34 journals and 6 items of a nonperiodical nature. The publications which contributed the major portion of the articles are listed below:

Journal	Number of Articles
(1) Doklady Akademii Nauk S.S.S.R.,	92
Comptes Rendus Acad. Sci., U.S.S.R.	38
(2) Journal of Physics, U.S.S.R.	117
(3) Journal of Technical Physics, U.S.S.R.	82
(4) Journal of Experimental and Theoretical Physics, U.S.S.R.	78

Journal	Number of Articles
(5) Journal of Physical Chemistry, U.S.S.R.	23
(6) Bulletin of the Academy of Sciences, U.S.S.R.	22
(7) Journal of General Chemistry, U.S.S.R.	13
(8) Elektrichestvo (Electricity), U.S.S.R.	[illegible]
(9) Zavodskaia Laboratoriia (Factory Laboratory)*	[illegible]
(10) Journal of Applied Chemistry, U.S.S.R.	6
Total	[illegible]

*Not published in 1941-1944.

The Doklady Akademii Nauk was printed simultaneously in Russian and in the French-English (called Comptes Rendus Acad. Sci., U.S.S.R.) language. The articles printed in Russian were usually more comprehensively written than were the French or English "translations". Sometimes, however, the Russian papers were abstracted in English, but this duality ended in 1947, at which time only the Russian edition (with no English abstracts) was printed. The Journal of Physics was printed in the English language, but its life was of short duration, namely, 1939-1947. The Journal of Physics was an organ of the Institute for Physical Problems of the Academy of Sciences, U.S.S.R., and printed papers concerning physical problems. It is believed that papers of this nature are now to be found in the publications of the Physics Institute, namely, the Journal of Technical Physics, U.S.S.R., and the Journal of Experimental and Theoretical Physics, U.S.S.R. Some papers also may be published in the Doklady Akademii Nauk which prints

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original research articles covering the fields of mathematics and all physical and biological sciences. In Doklady Akademii Nauk, papers are limited in length to four pages; this makes them comprehensive abstracts or summaries. Table III illustrates the period through which these journals have been active, together with the distribution of some articles of interest.

Also included in Table III are the Journal of Physical Chemistry, U.S.S.R., the Journal of General Chemistry, U.S.S.R., Elektrichestvo (Electricity), and the Bulletin of the Academy of Sciences, U.S.S.R. The interesting Zavodskaia Laboratoriia (Factory Laboratory) and the Journal of Applied Chemistry are not included in the table. The first two of these journals obviously concern chemistry. Elektrichestvo prints works in applied electrical engineering. The Bulletin primarily prints the minutes of the monthly sessions of the Academy, news of the various institutes, and reviews and critiques of papers presented to the Academy, and also includes the names of those people who attend the meetings. Zavodskaia Laboratoriia presents valuable works on a more practical, less academic level. All of the above appear only in the Russian language.

A survey of the articles collected indicates that no publication is dedicated to the interest of any particular group of semiconductors or to any particular line of study. The only restriction seems to be along the lines suggested by the titles of the journals.

Regarding the total number of references recorded from all journals, through the period from 1940 to 1951, it is thought that the English-language versions of the journals prior to 1947 made for wider

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TABLE III PUBLICATIONS AND DISTRIBUTION OF THEIR CONTENTS PERTAINING TO THE SEMICONDUCTOR ARTS: 1940–1951

Group	before 1940	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951
						Doklady Akademii Nauk S.S.S.R.							
General	-	-	-	-	-	-	-	-	-	4	3	5	6
Elements of Fourth Group of Atomic Table	-	-	-	-	-	-	-	-	-	-	-	-	-
Elements of Sixth Group of Atomic Table	-	-	-	-	-	-	-	-	-	-	-	-	-
Compounds	-	-	-	-	-	-	1	-	-	1	18	[illegible]	10
Other Materials of Interest	-	-	1	-	-	-	-	-	-	7	[illegible]	[illegible]	3
						Comptes rendus de l'Académie des sciences de l'U.R.S.S.							
General	-	1	1	-	1	[illegible]	1	[illegible]	-	[illegible]	2	-	-
Elements of Fourth Group of Atomic Table	-	[illegible]	-	-	-	-	-	-	-	-	-	-	-
Elements of Sixth Group of Atomic Table	-	-	-	1	-	-	-	-	1	-	-	-	-
Compounds	-	1	-	-	-	1	[illegible]	[illegible]	-	[illegible]	[illegible]	-	-
Other Materials of Interest	-	3	1	-	-	-	-	1	1	-	3	-	-

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TABLE III (CONTINUED)

Group	Before 1940	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951
Journal of Physics, U.S.S.R.													
General	2	6	28	3	4	5	10	7	1	-	-	-	-
Elements of Fourth Group of Atomic Table	-	-	-	-	-	-	1	-	-	-	-	-	-
Elements of Sixth Group of Atomic Table	-	1	8	-	-	-	-	-	-	-	-	-	-
Compounds	-	-	6	1	-	1	2	4	1	-	-	-	-
Other Materials of Interest	-	3	10	2	2	2	4	1	-	-	-	-	-
Journal of Technical Physics, U.S.S.R.													
General	-	-	-	-	-	-	-	-	[illegible]	8	5	1	4
Elements of Fourth Group of Atomic Table	-	-	-	-	-	-	-	-	-	-	-	-	-
Elements of Sixth Group of Atomic Table	-	3	1	-	3	-	4	-	-	-	1	1	1
Compounds	1	[illegible]	-	-	-	-	4	[illegible]	3	[illegible]	1	3	[illegible]
Other Materials of Interest	-	1	-	-	1	-	1	-	[illegible]	10	1	1	[illegible]

TABLE III (CONTINUED)

Group	Before 1940	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951
Journal of Experimental and Theoretical Physics, U.S.S.R.													
General	-	2	1	-	1	2	1	3	3	7	5	5	4
Elements of Fourth Group of Atomic Table	-	-	-	-	-	-	-	-	-	-	-	-	-
Elements of Sixth Group of Atomic Table	-	-	-	-	-	-	-	-	1	-	-	-	-
Compounds	-	1	-	-	-	-	2	-	5	3	6	9	1
Other Materials of Interest	-	2	-	-	-	-	-	2	2	[illegible]	2	5	-
Journal of Physical Chemistry, U.S.S.R.													
General	-	-	-	-	-	-	-	-	3	-	-	-	-
Elements of Fourth Group of Atomic Table	-	-	-	-	-	-	-	-	-	-	-	-	-
Elements of Sixth Group of Atomic Table	-	-	-	-	-	1	1	1	2	-	-	-	-
Compounds	-	-	3	-	-	1	-	1	1	3	2	-	-
Other Materials of Interest	-	-	-	-	-	1	-	-	2	1	-	-	-

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TABLE III (CONTINUED)

Group	Before 1940	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951
Bulletin of the Academy of Sciences, U.S.S.R.													
General	-	-	-	-	-	-	1	1	-	1	4	1	-
Elements of Fourth Group of Atomic Table	-	-	-	-	-	-	-	-	-	-	-	-	-
Elements of Sixth Group of Atomic Table	-	-	1	-	-	-	-	-	-	-	-	-	-
Compounds	-	-	1	1	-	1	-	-	2	-	4	-	-
Other Materials of Interest	-	-	1	-	-	-	-	-	1	-	2	-	-
Journal of General Chemistry, U.S.S.R.													
General	-	2	-	-	-	-	-	-	-	-	-	-	-
Elements of Fourth Group of Atomic Table	-	-	-	-	-	-	-	1	1	-	-	-	-
Elements of Sixth Group of Atomic Table	-	-	-	-	-	-	-	-	1	-	-	-	-
Compounds	-	3	-	-	1	1	-	-	1	1	-	1	-
Other Materials of Interest	-	-	-	-	-	-	-	-	-	-	-	-	-

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TABLE III (CONTINUED)

Group	Before 1940	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951
							Elektrichestvo						
General	-	-	-	-	-	-	-	-	1	-	1	4	2
Elements of Fourth Group of Atomic Table	-	-	-	-	-	-	-	-	-	-	-	-	-
Elements of Sixth Group of Atomic Table	-	-	-	-	-	-	-	-	-	-	-	1	-
Compounds	-	-	-	-	-	-	-	-	-	-	-	-	2
Other Materials of Interest	-	1	-	-	-	-	-	-	-	-	-	-	-
							Other Publications						
General	-	1	-	-	2	1	-	1	1	-	1	-	2
Elements of Fourth Group of Atomic Table	-	-	-	-	-	1	-	-	1	2	-	3	-
Elements of Sixth Group of Atomic Table	-	1	-	-	-	-	-	1	1	-	1	-	-
Compounds	1	1	-	1	1	-	3	2	3	4	[illegible]	1	1
Other Materials of Interest	-	-	-	-	1	2	-	-	2	1	-	1	1

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reviewing by those people who professionally review and abstract scientific writings (Physical Abstracts, Electrical Engineering Abstracts, British Abstracts, Chemical Abstracts, etc.). The task of reviewing articles written in other publications, in the Russian language, may have been found impractical from the standpoints of general interest and availability of competent Russian-reading personnel. It is also to be noted that, since about 1949-1950, the distribution of Soviet periodicals has been shortened and made more selective. Immediately checkable libraries report circulation to be sporadic, at best, tending toward complete stoppage of the flow of certain Soviet scientific literature.

In spite of this, the statistics for the latest years show an increasing number of articles reviewed or abstracted from the Russian language. This probably is due to heightening of interest in Soviet work and greater availability of reviewers through displaced-persons programs, etc.

3. Comments Pertinent to the Bibliography of Open Literature in the Period Between 1940 and 1951

In essence, the outline used in the World-Wide Digest of Literature on Semiconductors for 1950 and 1951 was used for the Soviet literature. However, there were two changes necessary. First, there were 11 years of Soviet literature investigated, so each subject heading had subheadings under it of years. Further, in order to obtain as thorough as possible a survey of solid-state research in the Soviet Union, consideration of metals and alloys (principally from the electrical standpoint) and dielectric materials was incorporated into the outline. Also, for clarity,

a few more detailed headings under the materials headings were used than in the Digest of Literature on Semiconductors.

a. Source of Literature

The principal sources of Soviet literature references were:

(1) Science Abstracts (Sections A and B)

(2) Chemical Abstracts

(3) Institute of Radio Engineering Abstracts

(4) Battelle Library Review

(5) British Abstracts

References were taken from these because they provide a convenient method of obtaining English-language abstracts of open Soviet literature. It should be noted that abstracts such as these usually do not provide information on the location of Soviet work or the authors. Also, the period through which the above abstract services have been in operation does not cover the 11 years from 1940 to 1951 in all cases.

Another source of information was an index to the English version of the Journal of Physics, U.S.S.R., for the years 1939 to 1946. Abstracts from this source were made by title only.

b. Organization of Literature

After all of the available literature was recorded, it was organized into an outline based on semiconducting materials and associated work. This outline is as follows:

It will be noted that the above outline takes in all known semi-conducting materials, as well as metals and alloys, organics, and theoretical work and applications. This outline has been put to practical use for some time in world-wide considerations of literature, both for research[1] and publication[2] purposes. It has been found to be of more value than other systems, i.e., those which are based on electrical components, alphabet, author, etc. The virtues of the system include easier compilation, more rapid selection, and easier access when required.

c. Use of the Literature

By using this method to categorize the Soviet literature collected, a general idea is gained as to where the emphasis of their work is located. Also, omissions or blanks might be indicative either of lack of interest or of the possibility that the work is being done on a secret basis, due to military interest. Information of this nature is more easily studied by putting the data into other forms, as is done in the following sections.

The names of pertinent foreign publications and the corresponding English titles are listed in Table IV. The complete bibliography of 523 references is given at the end of this report.

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(1) Used by the Semiconductor and Dielectrics Research Division, Battelle Memorial Institute, Columbus, Ohio.
(2) Semiconductors, Digest of Literature on Dielectrics, National Research Council, 1950 and 1951, Vols XIV and XV, Chapter 4.

TABLE IV CORRELATION OF THE FOREIGN AND ENGLISH TITLES OF PERTINENT PUBLICATIONS

Abbreviation	Transliterated Soviet Title	English Translation
1. Dokl. Akad. Nauk S.S.S.R.	Doklady Akademii Nauk S.S.S.R.	Reports of the Academy of Sciences
C. R. Acad. Sci., U.S.S.R.	Comptes Rendus de l'Academie des Sciences de l'U.R.S.S.	Reports of the Academy of Sciences
2. J. Phys., U.S.S.R.	-	Journal of Physics
3. J. Tech. Phys., U.S.S.R.	Zhurnal Tekhnicheskoi Fiziki	Journal of Technical Physics
4. J. Exptl. Theoret. Phys., U.S.S.R.	Zhurnal Eksperimentalnoi i Theoreticheskoi Fiziki	Journal of Experimental and Theoretical Physics
5. Bull. Acad. Sci., U.S.S.R.	Izvestiia Akademii Nauk S.S.S.R.	Bulletin of the Academy of Sciences
6. J. Phys. Chem., U.S.S.R.	Zhurnal Fizicheskoi Khimii	Journal of Physical Chemistry
7. J. Gen. Chem., U.S.S.R.	Zhurnal Obshchei Khimii	Journal of General Chemistry
8. -	Elektrichestvo	Electricity
9. J. Appl. Phys., U.S.S.R.	Zhurnal Prikladnoi Fiziki	Journal of Applied Physics
10. Zavod. Lab.	Zavodskaia Laboratoriia	Factory Laboratory

Note: The form of titles of the publications listed in the Bibliography is dictated by common usage.

SECTION IV

ANALYSIS OF SOVIET LITERATURE

This section is devoted to various types of analyses of the Soviet literature listed in the Bibliography. The information given in Section I, in particular the nature of the solid-state electrical-device field and the yardstick by which progress in it can be measured, is kept in mind in making all analyses of the literature.

Specifically, the Soviet literature is examined in several ways:

(1) From consideration of the omissions in the Bibliography, relative to the subject headings which were taken from the world-wide bibliography, information on omissions and concentrations of Soviet literature was obtained.

(2) Important information gathered from personal experiences with the Soviet literature in the past eight years was compiled into a digest of literature of sample articles for the 10-year period from 1940 to 1950. Such literature was chosen on the basis of experiences and highlighted items. This particular section is aimed at evaluating the particular state of knowledge in the U.S.S.R. and the technical quality of work in preparation for making analytical statements concerning the nature of classified literature in the Soviet Union.

(3) Thirteen of the more important articles of literature were studied and then thoroughly analyzed and criticized (Section V).

1. Materials Versus Years Study

As shown by Table V, the entire outline of the bibliography is listed with the number of publications in each category noted by the year of publication. Assuming the sampling of literature to be reasonably good, certain general ideas can be drawn from such a comparison.

Considering the over-all table, and specifically the totals for materials, the following can be said:

(1) A large number of theoretical publications are noted; this is a normal trend.

(2) Electrical properties of oxides, sulfides, selenides, and tellurides, as well as of other compounds, intermetallics, and metals, have been widely studied.

(3) Dielectric properties have been widely studied, particularly of the titanates. Work on titanates has been at a high rate since 1945.

(4) Work on luminescence and phosphorescence has been at a high level since 1947-1948.

(5) Nothing pertinent has been published on silicon or germanium or applications of these elements.

(6) Work on selenium has generally increased since 1945, although work on selenium rectifiers has been tapering off since 1947.

(7) Considerable work before and since the war is noted on compound semiconductors, such as oxides, sulfides, selenides, and tellurides. With some reservations, this also has been a trend in the U. S. since the war.

TABLE V LISTING BY YEARS OF NUMBER O[illegible]CATIONS IN EACH CATEGORY OF SEMICONDUCTOR-DEVICE A[illegible]ATED WORK

	Before 1940	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	Sub-total	Total
I. GENERAL															183
A. Surveys	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
B. Solid State in General	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
C. Electrical Properties	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
D. Rectification and Contact Phenomena	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
E. Light Phenomena	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
F. Dielectric Phenomena	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
G. Magnetism and Magnetic Effects	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
II. ELEMENTS OF THE FOURTH GROUP OF THE ATOMIC TABLE (C, Si, Ge, Sn)															12
A. Diamond and Carbon	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
B. Silicon	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
C. Germanium															
1. Conductivity	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
2. Bombardment-Induced Conductivity	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
3. Magnetoresistance	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
4. Rectifiers (Diodes)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
5. Transistors (Amplifiers)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
6. Photoeffects	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
7. Miscellaneous	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
B. Gray Tin	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
III. ELEMENTS OF THE SIXTH GROUP OF THE ATOMIC TABLE (Se, Te)															[illegible]
A. Selenium	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
1. Rectifiers	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
2. Photocells	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
B. Tellurium	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
IV. COMPOUNDS															[illegible]
A. Oxygen Compounds															
1. Zinc Oxide	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
2. Barium and Strontium Oxides	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
3. Ferrites	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
4. Copper and Titanium Dioxides															
a. General	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
b. Rectifiers	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
c. Photoeffects	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
5. Titanates	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
6. Other Oxygen Compounds	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
B. Sulfides, Selenides, and Tellurides															
1. Cadmium Sulfide	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
2. Zinc Sulfide	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
3. Lead Sulfide, Lead Selenide, and Lead Telluride	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
4. Other Sulfides, Selenides, and Tellurides	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
C. Halides	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
D. Carbides	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
V. OTHER MATERIALS															[illegible]
A. Metals and Alloys	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
B. Intermetallics and Elements of the Fifth Group of the Atomic Table	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
C. Organics	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
D. Miscellaneous	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
TOTAL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

(8) Work on alloys seems to have been shifted from copper-gold alloys to other alloys around 1948.

(9) Antimony and antimony compounds have been of greater interest since 1946. These materials have been shown to be semiconductors in some cases and are interesting particularly for their photo- and thermoproperties.

Looking at the table from the other aspect, namely, years, the following is noted:

(1) Total publications appeared to be at a relatively constant level prior to the World War II years.

(2) During the World War II years (1942-194[illegible]), publication dropped off, as would be expected.

(3) A build-up of publications is noted since 1947, with the highest numbers recorded in 1948 and 1949.

(4) A tapering off of publications is noted in 1950 and 1951. Data in 1951 are not considered too reliable because of Soviet restrictions on sending publications out of the U.S.S.R. and the usual time lag in the appearance of abstracts.

The statements regarding materials are made with the purpose of pointing out the areas of greatest interest. In general, these areas of interest coincide with those of the U. S., with the exception of the apparent lack of interest in germanium and silicon and the concentrated interest in compound semiconductors.

The trend of total publications as a function of years is exactly as would be expected, up to about 1947 - the end of World War II. Beyond this point, the indication may be false. One would expect a decrease in publication because of the "cold war" attitude; however, an increase is noted. This could be due to more complete coverage of Soviet work, since the U. S. interest in what they were doing was greater. On the other hand, it could be due to greater emphasis by the Soviets. Also, increased translation facilities are present in the form of displaced persons, etc. The drop off in publication since 1949 may be due simply to the Soviets' stoppage of technical material leaving their country, particularly in the fields of chemistry and physics. U. S. publication in this field follows the same trends until about the end of World War II (1946), and, from that time through 1951, a continuous and almost exponential increase in number of publications may be noted.

All of the statements discussed above should be tempered by the fact that it has not been possible to determine just what sampling has been made of all Soviet literature in this field. By comparison with a world-wide literature study in this field, it would seem that the total number of Soviet references collected represents a good sampling, showing the trend of their research if not a numerically accurate picture.

2. Digest of Selected Soviet Literature

In compiling a digest of selected Soviet literature, several factors had to be taken into account. Specifically, these were: (1) the scope of the solid-state-device field as presented in Section I, (2) the

character of literature studies (Section III) and the over-all Bibliography, and (3) an intimate knowledge of the present status of semiconductor-device research throughout the world.

Drawing strongly upon experience, about 40 per cent (194 references) of the over-all bibliography was selected as important enough to reference directly. In order to make comparisons, the outline of the World-Wide Digest of Literature on Semiconductors was used as a framework. The outline used in the digest, however, differs slightly from that used in the Bibliography. This arrangement was used principally to facilitate presentation of the high lights of the literature. Under each heading, the references were arbitrarily listed in order of years, with the later years last.

Some comments pertinent to the information contained in the digest are:

(1) In general, theoretical work has been extensive and of high level. Shifrin's theory, presented in 1944, spearheaded the field in consideration of transition materials. Pekar's Polaron Theory is of great interest.

(2) Some good experimental techniques and ideas have been indicated. Among these are (a) the use of Hall effect, resistivity, and thermoelectric-power measurements for the analysis of metals and alloys, and (b) a condenser method of detecting the sign of charge carriers as a tool for studying semiconductors and insulating photoconductors.

(3) Work on materials has been primarily on compounds and could be applied to various electrical devices. Lead sulfide and its use for thermoelectric generation was mentioned by Joffe in 1946. Bombardment of cadmium sulfide by electrons was done at an early date. Rectification in silicon carbide crystals has been considered.

(4) Photoconductivity and luminescence of semiconducting materials has been considered in great detail. Copper oxide, selenium, zinc sulfide, cadmium sulfide, the alkali earths, and the halides have received attention.

(5) Characteristics of ionic crystals have been considered. Among the halides, silver iodide and silver bromide were studied; the application appeared to be photography.

(6) Electrical ceramics and dielectrics have been extensively studied. In particular, the efforts of Vul and his associates on the titanates have been outstanding.

(7) Magnetism and magnetic effects in various solid materials have been of interest to the Soviets. They determined the galvanomagnetic effect in ferromagnetics to be caused by magnetization and not by induction. Ferromagnetic oxides (ferrites) were studied in 195[illegible]; thus, it seems that they may have started later than the rest of the world in the field. A photomagnetic effect was discovered early in connection with Cu_2O rectifiers.

(8) Semiconductivity in organics has been studied.

The preceding comments serve to mention a few of the high lights of the following digest.

I. GENERAL

A. Theories

1. Dealing With Solids in General

In 1940, Akhieser and Lifshits(126)* worked on the theory of electronic breakdown in ionic crystals in parallel with Froehlich, Seeger, Teller, and Von Hippel.

N. S. Akulov and L. V. Kirenskii(162) found theoretically a new magnetocaloric effect. They concluded that, when a ferromagnetic monocrystal is rotated in a strong magnetic field at low temperatures, strong periodic cooling and heating must take place. They verified this by experiments on nickel monocrystals at liquid-nitrogen temperatures. This new effect is quite different from the magnetocaloric effect of Weiss.

In 1940, Nikolaev(11) considered the unstable forms of the solid state and concluded that solids can be classified as amorphous, vitreous, and crystalline, the stability increasing and free energy diminishing in the order given. Also in 1940, Zaslavskii(13) investigated the dependence of crystalline structures on the chemical properties. He postulated that all halides, sulfides, selenides, tellurides, nitrides, phosphides, arsenides, antimonides, and bismuthides having the crystalline structure of

*Numbers in parentheses refer to items listed in the Bibliography.

NaCl, NiAs, or ZnS, when arranged in increasing order of their molecular volume, follow these rules: (1) All compounds of the NiAs type precede those of the NaCl type, and (2) the value of the absolute contraction of any compound of the ZnS type is higher than that of any preceding member of the NiAs or NaCl impurity.

Davydov[15] discussed concentration phenomena in semiconductors. He gives a theoretical discussion of the distribution of charges in semiconductors. A. F. Joffe[2] published a general article on semiconductors in 1941.

A survey of the work on the physics of solids in the U.S.S.R. was written by V. Kuznetsov[4] in 1941. Pisarenko[266] discussed Nernst's thermomagnetic effect in semiconductors and metals.

The lattice energy of ionic crystals was discussed in 1943 by Kapustinskii[19].

Frenkel[264] studied diffusion phenomena taking place during the formation of oxide films.

Superconductivity and particularly thermo electric phenomena in the superconductive region were studied by Ginzburg[5?]. I. I. Gurevich[58,174,175] postulated the carrying of electrons by phonon currents in 1945 and 1946 articles on the thermoelectric and galvanomagnetic properties of conductors.

In 1946, Lyshanov[61], in studying photoelectric effects, considered the distribution of electrical potential among atoms of a mixture.

Landau and Pekar[33] discussed the effective mass of the polaron in 1948. They assumed that the carrier of current in a crystal with an

ionic lattice is not an electron of the conductivity zone but a polaron. The conservative motion of a polaron as a hole was investigated. The dependence of the energy of a system on the velocity of the forward motion of a polaron and the equation of motion of a polaron in external fields were proposed. In 1949, Pekar[34] discussed the theory of polarons. He theoretically analyzed the polaron in an ionic crystal and studied the vibrations of ions through the use of quantum mechanics. The effective mass of a polaron and its forward motion were calculated. The waves of polaron structures possessing a continuous energy spectrum were obtained. The dispersion of polaron waves by optical vibrations of ionic character were analyzed, and the corresponding free path and mobility were calculated. The calculated mobilities according to their order of magnitude coincide with the measured mobility of current carriers in oxide and halide semiconductors.

Skanavi and Demeshina[151] reported a new form of dielectric polarization and losses in polycrystalline media. Specifically, the dielectric permittivity and loss angle of rutile with different impurities were determined. Low-frequency permittivity was 1,000 for the impurities calcium, strontium, ruthenium, and zinc. The activation energy of loosely bound ions showed abnormally low values. Thus, a new type of dielectric polarization was established.

In 1950, Pekar[35] considered a theory of the recombination of electrons in semiconductors. He considered the theory of recombination of the conductivity electrons in semiconductors on charged and neutral centers. The case where the probability of localization of an electron

approaching a center is sufficiently great for the rate of recombination to be limited and determined only by the diffusion rate of the electrons to the center of the recombination was investigated quantitatively. The recombination coefficient, the average displacement of the electron in an external field, and an electrical conductivity set up by irradiation of the crystal with ordinary light, X-rays, beta-rays, or corpuscular rays were calculated. These cases represent special cases of the general case of a disturbed thermal equilibrium of a semiconductor in which not even a satisfactory qualitative theory has been given so far. The treatment here is based on the author's Polaron Theory. Thus, it is applied to oxides or ionic crystals.

A seemingly good piece of work was done by Bonch-Bruevich and Tyablikov(39). They considered the theory of elementary excitations in a weak nonideal electron gas in a crystal. They found that the energy of the weakly excited state is the sum of the elementary excitation without interaction; this obeys Fermi's statistics. They also pointed out that the effective masses depend on the electron density in the lattice.

2. Electrical Conductivity and Hall Effect

Rudnitsky(40) studied the Hall effect in ferromagnetic bodies in 1939.

Davydov and Schmushkevitch(41) investigated the electrical conductivity of semiconductors with an ionic lattice in strong fields in 1940. They found that in a strong field the mobility of the electron increased in contrast to the decrease of the electron mobility in semiconductors with an

atomic lattice. The variation of mobility with field strength and temperature is different for low and high temperatures. They were led to this work by considering the thin, elastic collision ionizations of electrons, as well as the interaction of electrons with the optical vibrations of the lattice.

A. V. Joffe and A. F. Joffe[42] investigated semiconductors in strong electrical fields in 1940. It is a very important study and has to do with variations from Ohm's law at fields which tend to modify barrier layers. The apparent assumption here in carrying out this work is that perhaps there is a dependence of electrical properties on the barrier layers within the semiconductor and that they would like to find this. Conduction of semiconductors, such as copper oxide, selenium oxide, molybdenum sulfide, antimony oxide, tungsten oxide, and thallium sulfide was investigated and yielded values up to 10^5 ohm-cm at temperatures from -180 to +20 C. Ohm's law was obeyed in fields not exceeding 2,000 or 3,000 volts/cm. In higher fields, the conduction increases. With increase in temperature, the absolute increase in conduction rises slightly, but the relative increase becomes less. The photoelectric conduction in pure substances is independent of the fields. Presence of impurities will make it rise slightly with the fields. This is a very good article for this period of time. Davydov[47] made a theoretical investigation of the transitional resistances of semiconductors. The contact resistance of a semiconductor and a metal plate was calculated for currents of various magnitudes. He assumed that the conduction electrons have thermal energy only. The calculation was not meant to apply to copper oxide rectifiers,

and did not apply. The intertransitional resistances of a polycrystalline semiconductor were considered. They may sometimes decrease with an increase of current intensity. Kozhansky[167] discussed galvanomagnetic effects of semiconductors. The effect of the space charge should be taken into account when galvanomagnetic effects are studied in semiconductors. Theoretical considerations led to formulas necessary for the calculation of contact resistance of semiconductors.

Shifrin's[56] theory, which is applicable to lead sulfide, cadmium oxide, SnO_2, and others, antedates much work being done in the U. S. on transition semiconductors and theories for transition semiconductors. He proposed his theory in 1944. This suggests that in those days they were making studies that required a theory to explain the experimental results obtained. Nearby, in Germany, similar studies were also being made by Bauer, for example.

Pekar[67], in 1948, presented a new conception of the electronic conductivity of ionic crystals, namely, his famous Polaron Theory. This theory is as follows: Basic carriers of the conduction in ionic semiconductors are not electrons in the conduction zone but polarons, that is, self-localized electrons maintained in their state by the dielectric polarization of the crystal under the influence of the field of the localized electron. Transition from the zonal to the polaron state is accompanied by a gain of energy. In the electric field, polarons move like negative charges. Theoretical calculations of the mobility (μ) of the polaron lead to an expression from which the numerical value of μ for NaCl is estimated at 3 cm^2/volt-sec. The value of μ obtained from the Hall effect

and the photoconductivity is less than 8.3. Values of μ for copper oxide, molybdenum oxide, α-silver sulfide, and β-silver oxide from experimental data of electrical conductivity and the Hall constant, being in numerical agreement with those theoretically calculated for polarons, corroborate the predominance of the role of the latter over that of the zonal electrons.

Lushkarev(72) theoretically considered the diffusion of current carriers in semiconductors of mixed conductivity. Interpretation of the diffusion process was attempted. Analysis of the proposed equations resulted in the determination of the specific effect of rectification, the mechanism of which differs considerably from that of their operation and is connected with flooding or liberation by the current carriers of the forbidden layer.

Samoilovich and Konkov(181) considered what amounts to electrical analysis of metals. They pointed out that galvanomagnetic effects in ferromagnetics are determined by magnetization and not induction. They refer to Rudnitskii, who did some work in 1940 on explaining the Hall effects in ferromagnetics by the acceleration of such a spin-orbital force on the "d" electrons.

3. Barrier Layers, Rectification, Contact Potentials, Photoconductivity, Secondary Emission, etc.

In 1941, A. V. Ioffe and A. F. Ioffe(76) investigated the contact of a semiconductor with metals and found the dependence of the resistance of the semiconductor in contact with metals on the contact potential

difference. For high resistances, they found that the dependence was slight, but it is particularly strong for materials of low resistance.

Lusurov[77] presented a theory of diode detection in 1941.

J. Frenkel[33] proposed a theory of electrical contact between metallic bodies in 1945. In this case, he treats the electrical contact between two metals as a gap through which the electrons penetrate from one metal to the other by the mechanism of thermoelectric emission. This is increased by the lowering of the corresponding potential barrier under the influence of the image forces to an extent which is inversely proportional to the width of the gap. Such a theory gives a possible explanation of the increase of electrical conductivity of fine powders with increase of temperature in a manner similar to that of semiconductors.

Lukirsky[59] studied field emission in 1945.

Morgulis[64] theoretically analyzed the Schottky effect in complex semiconducting cathodes. He found certain phenomena occurring which are absent in ordinary metallic cathodes. He developed a new formula, differing considerably from the well-known Schottky formula, for use in calculating the total work function for electronic emission. This was a very good piece of work.

Karshchevskii[97] published on the anomalous internal photoelectric effect. He reported that the reduction of the electrical conductivity of a semiconductor upon illumination occurs in some, but not in all, samples of any semiconductor. The effect appears to be due to flaws and impurities in the crystal lattice. These flaws increase the volume polarization within the semiconductor and thus reduce the apparent conductivity. In

polycrystalline bodies, the negative photoelectric effect is more pronounced in strong electrical fields because photoelectrons stop at crystal boundaries and thus increase the polarization. In monocrystalline bodies, strong fields transfer photoelectrons to the electrodes without an increase in polarization. Flaws can be produced either by irradiation or during the preparation of the sample.

Schmushkevitch[86] investigated many features of semiconductors, including contact resistance. He claimed that he used chemically homogeneous semiconductors.

D. B. Gurevich and Tolstoi[116] divided photoresistors into exponential and hyperbolic classes, and Gurevich, Tolstoi, and Fofilov[117] have gone into great detail on dividing the photoresistances into these two groups - the exponential and the hyperbolic classes. They point out that copper oxide and cadmium sulfide are exponential at high temperatures, and bismuth sulfide, selenium, thallium sulfide, selenium selenide, and cadmium sulfide are hyperbolic at low temperatures. These three men are strong in the field of photoconductivity and semiconductors.

Lushkarev[119] discussed surface states relative to explaining the strong dependence of photo-emf on external fields. It is to be noted that this work is related to fundamentals. Lushkarev, in his studies of electrical field effects on photoelectric force, found that the photo-emf increased if the polarity of the external voltage coincided with the dark carriers of current. This is the so-called "condenser method".

4. Luminescence Phenomena, Miscellaneous

Pomeranchuk(129) theoretically investigated the thermal conductivity of dielectrics at temperatures higher than the Debye temperature. He showed that the Debye-Peierls curve obtained for high temperatures holds only for certain forms of dispersion of the velocities of the thermal vibrations and their dependence on the angle. In an ideal monocrystal, there is no anharmonic thermal resistance. Pomeranchuk(132) further investigated the heat conductivity of dielectrics at high temperatures where he considered the effects of quadruple collisions between photons due to cubic anharmonicity and the quadruple collision probabilities. He calculated these and determined the thermal conductivity of dielectrics as approximately proportional to $T^{-5/4}$ at high temperatures. His calculated values are in agreement with experimental values for NaCl, KCl, and quartz.

Antonov-Romanovskii(95) in 1943 indicated that the bimolecular scheme of phosphor luminescence gives satisfactory qualitative and partly quantitative interpretations of the phenomena observed in excitation of phosphors.

B. Experimental Determinations

1. Rectification and Contact Potential Differences

In 1948, A. V. Joffe(85) reported on the rectification at the grain boundaries of two semiconductors. Results were obtained in the experimental investigation of 10 different oxide-semiconductor combinations which indicate that good rectification action may be obtained by the single contact

of two semiconductors without heat treatment; thus, rectification is attained for the junction between P and N semiconductors.

2. Photoconductivity and Luminescence

Intensive fundamental studies were made of photoeffects and phosphorescence through the years from 1940 to 1950. Arsen'eva-Geil [illegible] presented experiments on the external photoeffect with semiconductors. He reported that energy distributions of photoelectrons with tellurium, silicon, indium selenide, cadmium selenide plus cadmium, and silver were determined. Semiconductors of the hole type, such as tellurium, and the electronic type, cadmium selenide plus cadmium, gave totally different curves which again differed completely from those for a metal layer, such as silver, whether thick or thin. The work functions of semiconductors systematically increase with increases in the energy of the light quantum effecting the removal of the electron.

Lashkarev(101) studied the longitudinal photoconductivity of semiconductors in 1948.

Borisov(142) in 1949 was using a silicon detector in his laboratory equipment for measuring conductivities and dielectric losses of crystallophosphors. This would indicate that silicon detectors are available in the U.S.S.R. However, no literature on investigations of silicon or its mechanism of conduction has been found.

It is interesting to note that Putseiko([illegible]) did experimental work to prove out Lashkarev's theory on the influence of electric fields on photoeffect in insulated semiconductors. Lashkarev points this out in a recent article printed in 1950.

Khlebnikov[118] published a comprehensive article on the basic properties and applications of photoelements wherein he described the various types of photoelements which had been developed in many years of research in the U.S.S.R.

3. Miscellaneous

Extensive studies of electrical and thermal conductivity of mono- and polycrystalline substances were made in 1944 by Mikryukov and Kutolnov[441].

Extensive studies of dielectrics aimed at applications of solid dielectrics in electrical fields at high frequency were carried out by the Soviets. Also, there were extensive studies of surface conduction on dielectrics[139,140]. A very interesting article was published by Kosman and Sozina[141] on dielectric constants of solid dielectrics at high temperatures. They discuss the existence of a high-voltage polarization emf in various types of insulating crystals, such as calcite crystals, beryl crystals, brick, granite, and mica. They found abnormally high dielectric constants, in the order of 1,000 to 3,000, at the higher temperatures. Thus, high-voltage polarization was proven to exist at high temperatures. Abnormally high dielectric constants seem to be the rule with all dielectrics heated to a temperature high enough to give rise to electronic conduction without perturbation of the lattice. However, the high values of the dielectric constants cannot be ascribed to volume polarizations, but must be ascribed to a nonuniform potential distribution within the samples, such as barriers.

Feranita[374] investigated the effect of impurities on electrical conduction in dielectrics at high temperatures. This is a very good paper. He pointed out that unipolar conductivity increases with increasing voltage, suggesting barrier-layer rectification effects and not polarization.

An interesting paper on one facet of the many peculiarities of ferromagnetic materials was written by Vonsovskii[68]. He treated the electrical conductivity of ferromagnetic substances at low temperatures. He pointed out that the electrical resistance is determined, in addition to collision between conduction electrons and phonons, also by collisions between electrons and Bloch spin-waves of ferromagnetic d-electrons. For these waves obeying Bose's statistics, the term "ferromagnon" is proposed. Analytical treatment of an approximate model of the ferromagnetic substance distinguishing between outer "s" electrons and inner "d" electrons shows that, at temperatures far below the Curie point, at magnetizations close to saturation, interaction between "s" electrons and "ferromagnons" gives rise to an additional electrical resistance specific to ferromagnetic substances and proportional to T^3. Experimental confirmation is impossible, owing to lack of the necessary experimental data.

Vodopyanov[153] discussed dielectric losses of certain crystal specimens at a high frequency. He points out that it is necessary to establish the connection between the electrical characteristics and the composition of the dielectrics and their physical-chemical properties. Therefore, he conducted tests on crystal dielectrics with ion conductivity and crystals with polar molecules of simple and complex structures to determine the relation of the angle of [illegible] the frequency and

temperature. In the first group of crystals, the dielectric losses should be specified by the progressive transposition of electric charges. The dielectric crystals of polar molecules can have losses of dipole nature if it is possible to orient the dipoles in an alternating electrical field. The angle of loss in the dielectric crystals is very small, and the measurement of the loss is done with great difficulties. This explains why so little is known about dielectric losses in crystals. The results indicated that dielectric losses in crystal dielectrics with ionic conductivity, such as sodium chloride, quartz, etc., are determined completely by electrical conductivity, that is, the nature of the dielectric losses is ohmic. Modern measuring methods show the absolute value of the angle of loss in a crystal of sodium chloride to be 10^{-5} radian which exceeds the value calculated from the conductivity in the constant electrical field 10^{8} times.

Of interest is the article written by Boltaks[248] where he criticizes Henisch's work on TiO_2 and says he is wrong in regard to saying that one cannot use a thermal emf for determining the sign of charge carriers. He blames Henisch's experimental techniques for this conclusion. Boltaks mentions that his findings agree with Davydov and Shmushkevich's theories on thermal emf.

C. Methods, Techniques, Applications

A. F. Joffe[3] discussed various aspects of the years of semiconductor work which were leading to technical developments. In particular, detection of high-frequency currents, rectification of a-c voltages,

photoelectromotive forces, and photoresistances were indicated as technical applications. From the content of this article, it is to be expected that the Soviets had a strong semiconductor group, even as early as 1[illegible]. This suggests that they did not confiscate their knowledge entirely from Germany in 1945. Joffe attributes the reduction to practice of Cu_2O and selenium rectifiers to Levinson and Sharavskii. Also, he attributes to [illegible] and Kukaev the invention of a new type of rectifier using Cu_2S and magnesium.

Schutnikov(133) indicated in an article in [illegible] that they had produced piezoelectric elements for electrical and acoustic equipment.

There were many studies of oxide films made on aluminum, using all types of methods. Godes and Lutin(202) investigated the electrolytic condenser in 1945. They described an Al_2O_3 condenser of one-third to one-quarter smaller size than units previously made, in which metallized tissues were used for fabric. They rolled the tissue with 100 [illegible] paper, inserted it in an aluminum tube, and then impregnated the tissue with a higher [illegible] temperature-stabilized electrolyte. They compared them to four manufacturers' condensers and found that these were better.

An article by Savchenko(56) illustrates how much was known about luminescent materials in the U.S.S.R. in 1945. The article indicates that permanently luminescent materials are not sufficiently bright. Lacquers reduce the brightness to one-half or one-third. ZnS materials in contact with iron blacken rapidly and must be protected by anticorrosive coatings. Lacquer solutions lose 3[illegible] percent of their brightness when immersed in H_2O or irradiated with a mercury arc. Temporary phosphors, calcium sulfide

with copper, and strontium sulfide with bismuth are bright enough, but can be used only for short times as they are sensitive to H_2S and temperature. A special composition of ZnS and copper with a long phosphorescence is recommended for blackout use. For short periods of time, organic luminescent colors can be used.

In 1946, Akimov[62] described a point-contact device for determining microthermoelectromotive forces. He used this in connection with studies of metals.

Andreev[143], in 1947, discusses piezoelectric crystals and their uses.

A rather interesting article on the true conductivity of solid dielectrics was written by Gorelik and Dmitriev[145]. They presented a method of determining the true conductivity which is intrinsically different from the conventional ones already presented. This included the determination of the emf of polarization for the whole range of its existence. The increase of the conductivity in the domain of the emf of polarization was proven to be consistent with Joffe's theory.

Ryvkin[102] presented a rather interesting method of investigating photo emf's using a condenser arrangement. He described the theory of this method of investigating the photoelectric properties of semiconductors. He indicated that, under certain conditions, this method may be applied to the investigation of the true photoelectromotive force for obtaining the sign of the current carriers. A very important article was written by Zhuze and Ryvkin[103] in 1948, which showed that the crystal photoeffect is suitable for determining the sign of charge carriers. They used a condenser

method and found that they got negative photoelectrons in bismuth sulfide, thallium sulfide, antimony selenide plus 2 per cent antimony, cadmium sulfide, lead oxide, mercury sulfide, mercury iodide (HgI and HgI_2), silver sulfide, zirconium sulfide, and zirconium selenide. They found that they obtained positive photoconduction in copper oxide, selenium, bismuth selenide, tin sulfide, tin selenide, molybdenum selenide, thallium selenide, antimony selenide plus 2 per cent selenium, indium selenide, lead iodide, and uranium selenide. They found that the sign of the photo-emf is the same as that of the thermal emf in all cases. This is a good illustration that materials control is the "life blood" of solid-state research.

An article by Brumbery and Feferman[337] on a luminescence method for investigating the absorption spectra of crystallophosphors illustrates the very detailed nature of the studies which the Soviets are making on phosphorescent materials. It was pointed out in this article that the difficulties involved in the determination of absorption spectra of crystalline powders caused Vavilov to propose the use of ultraviolet-light photomicroscopes provided with a special spectrographic adapter for the study of small single crystals. In this way, the diffusion scattering inherent in powders is avoided, and use of very thin crystals permits the exploration of the far ultraviolet. Using this procedure, they measured the absorption spectra of ZnS, ZnS-Cu, ZnS-Cu, and ZnS-Cl phosphors in the wavelength range 465 to 254 mμ.

Hush, Meyants, and Fabelinskii[349] used ... Roberts' and von Hippel's method of measuring the temperature dependence of permittivity

and loss angle of dielectrics in the centimeter wave range but claim that they modified it so that it was much simpler.

From an article written by Morozov[9] on manufacture of capacitors in the Soviet Union, it can be concluded that capacitor research is progressing well in the U.S.S.R. under a five-year plan. Capacitor development and manufacture is faced with a shortage of good personnel. Standardization in the capacitor industry in the U.S.S.R. is still incomplete, miniaturizing is still to be done, and paper power capacitors are used extensively. There was no indication in this article of any work on tantalytic capacitors, barium titanate capacitors, or glass capacitors.

Tolstoi and Feofilov[113] are also working in the field of luminescence, besides working in the field of photoconductivity.

II. ELEMENTS IN THE FOURTH GROUP OF THE ATOMIC TABLE (C, Si, Ge, Sn)

A. Diamond and Carbon

The only work found in the Soviet literature on the fourth-group materials was on diamond. In this case, Simane[185] of Czechoslovakia studied some Brazilian diamonds and found results somewhat similar to those of Danielson's at Iowa State University.

B. Silicon

No references were found in this category.

C. Germanium

No references were found in this category.

1. Conductivity

2. Bombardment-Induced Conductivity

3. Magnetoresistance

4. Rectifiers (Diodes)

5. Transistors (Amplifiers)

6. Photoeffects

7. Miscellaneous

In 1940, work was done[190] on attempting to find germanium in coal.

D. Grey Tin

Grey tin was not mentioned as a semiconductor in any of the literature found. In 1945, Sharvin[194] investigated the superconductivity of grey tin down to 1.32 K. Jovanovic[195] discussed grey tin in 1947.

III. ELEMENTS IN THE SIXTH GROUP OF THE ATOMIC TABLE (Se, Te)

A. Selenium

1. Rectifiers

By 1946, it was apparent from the Soviet literature[(210,211,212)] that they had made extensive studies of selenium rectifiers. Levinson[(213)],

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in 1941, came out with the formula for the high-voltage selenium rectifier, using shellac, cellulose, lacquer, etc., as artificial barrier layers on the selenium. It is to be noted that this was somewhat earlier than such artificial barriers were being considered in the U. S. Nasledov[217] implied that selenium rectifiers contain a blocking layer of amorphous selenium as early as 1945. He talked about a 100-volt breakdown voltage. A good article was written by Fenin and Astakhov[219], in 1946, on selenium rectifiers with metal selenide additions. They pointed out that as little as 0.01 atomic per cent copper, nickel, or silver in the selenium is enough to stop rectification.

An extremely interesting article on metallization of liquid selenium was written by Urazovskii and Luft[207] of the Institute of Chemical Technology at Kharkov. They assumed that both liquid and metallic selenium are mixtures of two different selenium molecules and that metallic selenium obtained from different melts would contain different proportions of these. They used electrolytic methods and also organic agents, such as quinoline, pyridine, and aniline and diethylamine, to influence the rate of metallization. This is a very important part of the work, since it points out that the Soviets knew or appreciate the relationship between selenium and various organics. The results of their electrolysis work suggested that the melt might contain selenium selenide. They found that selenium from the cathodic compartment in their electrolysis experiments showed high conductivity, while that from the anodic compartment was nonconducting, formed no X-ray pattern, and was very slowly metallized by quinoline. Another article, written by Urazovskii, Polatnik, and Luft[208] in 1948, on

metallization of liquid selenium, showed that electrolysis and the use of quinoline might be very useful in making vitreous selenium layers. X-ray patterns of metallic selenium obtained by annealing at 1[illegible] C or by the action of quinoline on glassy selenium at 25 C appeared to be identical.

2. Photocells

b. Tellurium

No references were abstracted in this category.

IV. COMPOUNDS

A. Oxygen Compounds

1. Zinc and Cadmium Oxides

In 1948, Kudryavtseva and Sinyavskina[234] found that [illegible], [illegible], and TiO_2 would not partake of thermal radiation due to peculiar absorption characteristics. Veselovskii published, in 1948, on both zinc oxide[235] and silver oxide (Ag_2O)[311] in regard to photoelectrochemical processes occurring between Zn-ZnO and $Ag-Ag_2O$ (photogalvanic action).

Sokolov[236] published on the thermic nature of the glow during oxidation of zinc and noncandoluminescence of zinc oxides. He attempted to prove whether Nichols' hypothesis about the excited luminescence of oxides in a plane, which in contrast to thermal luminescence is called candoluminescence, was correct. Therefore, Sokolov attempted to solve the question on existence of candoluminescence for a[illegible] wire and in a petrol flame; his result was negative.

2. Barium and Strontium Oxides

Gorelik[236] studied barium oxide cathodes in 1945.

3. Ferrites

As an example of work on ferrites, Toropov and Borisenko[239] studied solid solutions in the nickel oxide-ferric oxide system. Intensive studies were made of the mixing on nickel thermal effects, the first two at 180 C and 340 C, corresponding to a loss of hydroscopic and of crystal H_2O, respectively, and the third at 815 C corresponding to $Ni_2O_3 \longrightarrow 2\ NiO + 1/2\ O_2$. On account of this dissociation, it is irrational to use Ni_2O_3 for the production of nickel ferrites. Drying, firing, and pressing at high temperatures was carried out for large numbers of ratios of NiO to Fe_2O_3. Petrographic examination revealed a one-phase structure only for molecular ratios of 1:1 and 2:3. With molecular ratios of 3:2, 3:1, and 2:1, the products showed two phases, one of which was identified as nickel ferrite, the other as NiO. X-ray diagrams were obtained showing disappearance of Fe_2O_3 lines in the 2:1 product and also of NiO in a 1:2 and 2:3 product. A similar study was made for CoO-Fe_2O_3 ferrites[240]. This was a high-technical-level type of investigation.

4. Copper and Titanium Oxides

Considerable work was done by various people on investigating the characteristics and preparation of rectifiers and the properties of copper oxide in the year 1940.

Bukreev[250] reported on annealing copper oxide rectifiers in a chemically inert atmosphere containing nitrogen and water. He pointed out that this is intended to improve the electrical characteristics of the rectifier. [illegible][251] showed that the copper oxide rectifier changes sign of rectification in the temperature interval of 32° to [illegible] C, depending on the kind of rectifier. This phenomenon does not depend on (a) whether the upper electrode is copper or gold, (b) the atmosphere in which the rectifier is heated – air, nitrogen, or vacuum, or (c) the speed of heating (3 minutes to 3 hours). Kraus and [illegible][illegible] studied the breakdown potential for copper oxide rectifiers. They used 41-mm-diameter plates and found 64 volts for one and 7[illegible] volts for [illegible] the breakdown. The breakdown potential tends to increase with increasing outside diameter. Introducing small quantities of chlorine into the high-temperature furnace considerably improved the electrical characteristics of the rectifier. This work tends to indicate that the Soviets could make a good copper oxide rectifier in 194[illegible].

In 1940, Li[illegible]schenko[241] showed that copper oxide polarizes at low temperatures, namely, -183 and -[illegible] C. Marchenko and [illegible][illegible] showed that the Schottky theory of rectification is not applicable to copper oxide rectifiers in the low-resistance direction. V. [illegible] [illegible] and Broido[255] showed that silver plating in the place of [illegible] improved the stability of the copper oxide in humid atmospheres. [illegible][illegible] showed that variation of oxygen content from 2[illegible] to 1[illegible] per cent in [illegible] in the tempering furnace did not affect the forward and reverse currents.

Also, in 1940, he studied the equivalent capacity of copper oxide rectifiers in an impulse circuit(257).

Electrical conductivity of Cu_2O_3 and the thermoelectric power of Cu-Cu_2O_3-Cu couples were studied by Zhuze and Starchenko(242) in 1940. They found a peak in the thermoelectric power at 45 C.

Photoeffects of copper oxide were also considered in the early 1940's. Lashkarev, along with Kosonogova(258), studied the influence of impurities on the rectifier photoeffect in 1941.

An original article which demonstrates the technical ability of the Soviets was written by Kikoin and Simonenko(259) working in the Physical Technical Institute of Sverdlovsk. This article dealt with the effect of the magnetic field on the photoconductivity of the semiconductor. They found a photoelectromagnetic effect in the case of copper oxide, where $\Delta R/R$ varied 28 per cent from zero to 8,000 oersteds at liquid nitrogen temperature. The effect is one of reducing the photoconductivity of copper oxide. This demonstrates the detailed nature of the solid-state studies carried on by the Soviets, since such effects could only have been found as a result of detailed studies.

A large amount of work was done during the period 1948-1950 by such men as Lashkarev, Kosonogova, Zhuze, Ryvkin, and Fedorus. Lashkarev and Kosonogova(260,261) studied the photoelectromotive forces in copper oxide, showing that they could divide it into that controlled by electric fields and that not controlled by electric fields. The sign of the emf is determined by conditions prevailing at the contact of the metal and the semiconductor. Lashkarev and Fedorus(262) presented data showing the

nonlinearity of photocurrent in copper oxide as due to the influence of light on the lifetime of the carriers. The effect is greater the longer the lifetime of the carriers. They expect that the light shifts electrons from levels with long lives to levels with short lives. Ryvkin[263] investigated the photoconductivity of copper oxide. His results indicated that he should study the temperature dependence of (1) light, [illegible], (2) quantum yield, [illegible], and (3) stationary photoconductivity, [illegible]. Zhuze and Ryvkin[264] worked on the mechanism of photoconductivity of copper oxide. In this case, an attempt is made to explain some incongruities of the results of some previous work by Ryvkin. They suggest a zonal scheme based on the hole character of the dark conductivity, holes being created in the lower zone by a thermal transfer of a portion of the electrons to acceptor levels of the oxygen. The photoconductivity has been produced by a transfer of electrons under the influence of light from acceptor levels into the higher zone. Also, Ryvkin[265] measured the quantum output of internal photoeffect in Cu_2O in 1950.

The above studies, which have been carried out by several outstanding people, are of a very high technical nature, suggesting much available background, just as the literature of the early 1940's indicates.

Titanium oxides have been studied very diligently and thoroughly in the U.S.S.R. by many people. Apparently, there were rather intensive chemical studies carried out about 194[illegible], as shown by an article on studying TiO_2 for evidence of brookite structure by [illegible] and [illegible]va[illegible].

It is interesting now to note that the work started by [illegible][illegible], which ended in the discovery of barium titanate, was on dielectric

permeability of rutile mixtures. His objective was to find a material which would exhibit a temperature coefficient of dielectric permeability of zero, which would be an important aid in making electrical condensers for use in operating circuits whose frequency is to be invariant with temperature. He started out studying calcium oxide and magnesium oxide, and combining them chemically with the titanium dioxide. This gave him good results; he found both negative and positive temperature coefficients of dielectric permeability.

Studies of the catalytic properties of titanium dioxide and also of the polymorphism of titanium dioxide were made by Rubinshtein and Kulikov in 1949[246]. This brought to mind that the Catalytic Conference in the U. S. (the Gordon Conference) mentioned the importance of semiconductor technology in catalysis work.

There was one indication that the Soviets are not studying TiO_2 for rectifiers, given by an article on electrical characteristics of TiO_2 by Knendzov, in which he mentioned that the U. K. and the U. S. were studying TiO_2 for rectifiers. It was mentioned in such a manner as to indicate that they probably were not doing such work in the U.S.S.R. to the writer's knowledge.

5. Titanates

Preparation of titanates was going on in 1949 in the U.S.S.R., as indicated by an article on kinetics of formation of lead titanate by Pamfilov and Fridman.[266]. Some 15 to 20 articles of very good scientific nature on barium titanates and titanates in general were written in the U.S.S.R. during the period from 1945 to 1950, primarily 1945 to 1947. Some chemical work apparently was done in 1949, as indicated by the publications.

This all fits a pattern and suggests that excellent scientific investigations were carried on by the Soviets in this field.

Ginzburg[267] discussed the dielectric properties of crystals of Rochelle saltlike substances, namely, barium titanate, in 1945. Vul[268,271], working alone and with Goldman[272], mentioned in 1945 the nature of the dielectric constant of some titanates, particularly beryllium, magnesium, calcium, zinc, strontium, cadmium, and barium, and indicated their high dielectric constants which he measured from -190 to +320 C[269]. Vul also measured the dielectric constant of barium titanate at temperatures of 4 K. He showed that dielectric constant is a function of the strength of alternating fields in the range 7 kilovolts per cm. He mentioned the use of barium titanate in condensers. In other articles[270,273], with Goldman and Vereshchagin respectively, Vul investigated the dielectric constants of barium titanate as a function of pressure between 300 and [illegible] atmospheres. He pointed out that barium titanate has a dielectric hysteresis and gave the pressure coefficient for dielectric constants.

Ginzburg[300] discussed the properties of ferroelectric crystals of the Rochelle salt type, the phosphate and arsenate type, and barium titanate. Transition of the Curie point from a nonpiezoelectric crystal into a piezoelectric one is a phase transition of the second kind, and the theory is treated thermodynamically. In distinction from other ferroelectric crystals, the piezoelectric phenomenon of barium titanate is impossible above the Curie point. The Curie point is also the transition point from the piezoelectric to the nonpiezoelectric state.

To Vul and Joffe is attributed the discovery of high-dielectric-constant barium titanate. This was recognized by G. Stanley Smith[274] in an article in Chemical Age in 1945.

Following this large number of articles, a rather intensive investigation was indicated. More detailed studies of barium titanate and what causes high dielectric constants and other interesting properties were engaged in by Vul and others[275,276,277,278].

Mash[279] reported on the losses and dielectric permeability of barium titanate in fields of high frequency. High-frequency investigations of barium titanate were reported by Novosilitsev and Khodakov[280] in 1947. At about this time, 1947, Skanavi[281] began intensive work on the problem of the high dielectric constants of some crystals, such as TiO_2 and barium titanate. Here Skanavi was principally interested in explaining the high dielectric constant of these crystals. Further[282], in 1948, he discussed barium tetratitanate and other dielectrics of the system TiO_2-BaO, and considered the dielectric problems of this whole system. Other people came on the scene in 1949, such as Avertukh and Kosman[283], investigating the dielectric properties of barium titanate. Ginzburg[284] reported additional work in 1949. Khodakov[285] also reported studies on high-frequency effects on barium titanate. Kulkarni-Dzhatkar and Yativadzhu-Iengar[313] were, in 1950, studying dielectric permittivity of ferroelectrics.

6. Other Oxygen Compounds

As early as 1941, some of the electronic semiconductors were studied as a function of dissociation, that is, electrical conductivity

as a function of chemical dissociation. This is very interesting, since it indicates a "marriage" of physics and chemistry at that time in the U.S.S.R. which was not common in the U. S.

Mileeva and Mokeev(289), in 1941, were studying the behavior of solid electronic semiconductors.

Primary Al_2O_3 was classed with amorphous substances in 1942 by Dankov, Kochetkov, and Shishakov(291). These investigators' conclusions were that this material needed much more study.

Also, in 1943, Pamfilov (recall him from the TiO_2-lead titanate work), who was working with Fridman(292), published on studies of the crystal modifications of lead oxide (PbO). He compared these structures to the TiO_2 structures. It is to be noted that rather extensive studies of the solid state were in progress among the chemistry people in the U.S.S.R. at this early date.

Secondary electron emission of Al_2O_3 films was studied in 1944 by Zernov, Elinson, and Levin(295). They pointed out that Cs_2O doping causes electron secondary emission.

MgO was studied by Zernov in 1945(297) in a detailed work which is very good.

In 1947, in Hungary, the perovskite-structure family was investigated by Naray-Szabo(303). He investigated borates, zirconates, cerates, aluminates, chromates, and stannates and showed that some belonged to the perovskite family.

In 1948, Potinyan(308) investigated the action of H_2S on such oxides as PbO_2, MnO_2, and HgO, his great interest being in the change in rate of diffusion as a function of time.

A very interesting article on electron emission produced in thin layers of B_2O_3 by bombardment with positive ions was written by Starodubtsov[309] in 1948. The effect was discovered by Malter in 1936 and published in the Physical Review, 1935, Vol 49, p 378. It is attributed to the positive charge created on the dielectric surface.

Advanced studies of ferroelectrics were made by Kulkarni-Dzhatkar and Gopalaswami[314]. They found that KH_2PO_4, $NH_4H_2PO_4$, KH_2AsO_4, and $NH_4H_2AsO_4$ were ferroelectrics.

B. Sulfides, Selenides, and Tellurides

1. Cadmium Sulfide

Arkhangelskaya and Bonch-Bruevich[327] must be good experimentalists. They considered the effects on cadmium sulfide under irradiation with electrons, just as others in the world are doing. They deduced that cathodic conductivity developed by bombardment follows approximately a bimolecular law.

2. Zinc Sulfide

A very detailed article on the interaction of zinc and manganese activators in zinc sulfide - manganese phosphors was written by Levshin[328] in 1947.

Fridman, who was working with Pamfilov on titanate preparation in 1940 to 1943, appears in 1948[330] working on phosphors (zinc sulfide luminophors). He was working as a senior research man, with Cheremnev helping

him. Fridman reported on a new stable zinc sulfide luminophor having long duration of afterglow, better than shown by earlier ZnS luminophors or by the alkali-earth-metal sulfide luminophors.

Fil[340,341] is quite an investigator of phosphorescence, spending a lot of his time on zinc sulfide, the introduction of copper into it, and the dependence of the luminescence yield on temperature and its connection with other properties. In 1949, he was associated with Ortman.

Timofeeva[112,343] investigated the effects of alpha-ray bombardment on zinc sulfide in 1949. She presented some data on mechanisms of luminescence of semiconductors.

3. Lead Sulfide, Lead Selenide, and Lead Telluride

Deviatkova, Maslakovez, and Seminsky[350] worked on the thermoelectric effect in PbS in 1941. Dunaev[351], in 1946, measured the heat conductivity of PbS, and Dunaev with Maslakovez[352] worked on PbS in 1947. In a recent article by Putley, in the <u>Proceedings of the Physical Society</u> of 1951, he refers to work thus done in 1947, wherein they measured the Hall effect and conductivity, and points out that these men did not find evidence of intrinsic conductivity in lead sulfide such as Putley did. It can be construed from this that the lead sulfide used by the Soviets at this time was not pure or stoichiometric. This would imply that production of lead sulfide was also poor. One cannot carry this type of argument too far, however, since lead sulfide is a very sensitive material to all types of treatments.

To show that Lashkarev, Kotapenko, and Fedorus are "on the track" so far as lead sulfides are concerned, it is of interest to note that, in one article on the photoconductivity of lead sulfide photoresistances, published in 1949(355), they pointed out that their lead sulfide was different from ordinary bulk-produced lead sulfide.

Nukrashevich and Fisher(87) investigated the dependence on frequency of unipolar conductivity of a contact in a lead sulfide crystal rectifier. Curves of rectifier current versus amplitude of applied voltage and frequency were obtained for electronic and for hole conductivity. An inversion of the rectification effect occurs at definite relations between frequency and amplitude of the applied voltage. An equivalent tube circuit is presented, demonstrating the behavior of the detector considered.

Sosnowski(356), in 1949, reported on a new method of preparing photoconductive and photovoltaic lead sulfide cells. This was essentially a discovery of a new type of photovoltaic effect wherein the emf is generated within the layer of the semiconductor. It is an effect which today is recognized as a barrier-layer photoconduction effect. In this article, an explanation of the photoconductivity was presented wherein the controlling influence was attributed to intercrystalline contacts in the sensitive layer. Theoretical values of conductivity, rectification, sensitivity, photo-emf, and time of response were found to be in satisfactory agreement with experimental data when the theory of this explanation was used.

There was nothing about thermoelectric generators in any of the Soviet literature which was studied. However, in view of the extensive studies by the Soviets of such things as lead sulfide, it would appear that they could have thermoelectric generators.

4. Other Sulfides, Selenides, and Tellurides

Sulfide rectifiers are reported by Dunaev and Kurchatov[358] in 1940. (Note this early date.) They pointed out that the most favorable working temperature for these rectifiers is between 100 C and 120 C. These rectifiers have a capacitance of 0.08 to 0.8 microfarad. They also pointed out that all phenomena observed in sulfide rectifiers agree with the theory of the electronic rectifying mechanism proposed by Davydov and Schottky.

Geichman and Soroka[361] reported on a silver sulfide rectifier photocell in 1941. Also, Kupchinsky[362] reported, in 1941, on the principal properties of thallium sulfide resistances. Il'ina[364] published on the application of silver sulfide photocells in spectrophotometry. Fourteen types of barrier-layer AgS photocells were investigated. It was found that instability was completely absent and also that no frequency dependence was observed between 25 and 2,500 cycles. They have a negative temperature coefficient between 5 and 50 C with a maximum response at 850 $m\mu$, and a threshold at approximately 1,400 $m\mu$. Note that this article indicates that they probably have these photocells in production.

Kolomietz[365] described the manufacture of thallium sulfide photocells.

Lashkarev and Potapenko[109] were active in working on lead sulfide, thallium sulfide, and silver sulfide in regard to the kinetics of photoconductivity in them. This sounds as if it might be related to infrared uses.

Anikina and Antonov-Romanovskii(371) were apparently working with alkali earth phosphors.

Galperin(459) suggested that the tellurides of chromium are very interesting from the magnetic point of view.

A photoelectric resistance of bismuth sulfide having maximum sensitivity in the visible range of the spectrum was described by Kolomiets(374).

C. Halides

In general, it can be said that a very large amount of work is being done on halide phosphors, sulfide phosphors, and alkali-earth phosphors.

Studies were made in 1942 by Kikorskii(382) on the dependence of dielectric losses on the nature of the electrical conductivity of halide crystals. He points out that dielectric losses are determined by nearly free electrons in the crystals where the electrical conduction is linked with the closely bound electrons of the atoms. This may be the basis for the Polaron Theory of Pekar.

It is of interest to note that in Barshchevskii's(388) studies of light absorption in thin layers of silver halides, namely AgI and AgBr, he made films 10^{-6} to 10^{-5} cm thick. In his results, he infers the relationship of his thin-film results to latent-image formations, such as in photography.

Another article by Goransova, Rapoport, Shapiro, and Sheninker(393) dealt with the study of crystal ionization chambers. It might be concluded from this that they were studying AgCl crystal counters in 1950.

It was noted that in some of the work by Meiklyar and Putseiko(395), wherein they studied the photoelectric and optical properties of silver halide crystals, the use of the condenser method of Putseiko was prominent. Also, they had a photoelectric spectrophotometer in their laboratory for taking

other data. It should be noted that the latter is an excellent piece of equipment to have in any solid-state laboratory.

D. Carbides

Karayazopulu and Novikov(402) reported, in 1940, that the Soviets could satisfactorily produce SiC "p" units which were being imported prior to that time.

Lossev(403) pointed out, in 1941, that SiC single crystals were available. He gave data on rectifier photoeffects in such crystals.

Pruzhinina-Granovskaya(413) was one of the persons studying the rectification of silicon carbide.

Zagyanskii, Samsonov, and Popova(414) prepared single crystals of SiC, and also of B_4C. These were about 10 by 10 by 0.5 millimeters in size. They used B_2O_3 and carbon black as starting materials and obtained dark and opaque crystals.

V. OTHER MATERIALS

A. Metals and Alloys

The Soviets have applied electrical analysis methods, such as the Hall effect, resistivity, and thermoelectric power, to metals and alloys. They were able to detect changes in these metals and alloys, such as changes in ordering of the crystals, changes due to stress, etc.

Serova investigated(4[illegible]) the electrical conductivity of monovalent metals. Using the wave functions of the conductivity electrons generally

used in the calculation of band forces and other characteristics of monovalent metals, he calculated the electrical conductivity and obtained considerably better agreement of the calculated and experimental values than those which Bardeen calculated in 1937.

Galperin[442] studied interatomic distances in ferromagnetic metals and carbides, nitrides, borides, etc., aiming at obtaining an understanding of ferromagnetism.

Komar[420] studied the resistance, in a transverse magnetic field, of an $AuCu_3$ alloy in the ordered and nonordered states. In 1941, Komar and Sidorov[428] published on the Hall coefficient of $AuCu_3$. Also, Komar[426,427, 437,438] made extensive studies of the electrical conductivity and galvanomagnetic properties of $AuCu_3$ alloys between 1941 and 1943.

The $PdCu_3$ alloy was studied by Sidorov[444] in regard to the conductivity and Hall effect and also by Komar and Fortnyagin[457] in 1948.

Smirnov[447], in 1947, discussed the theory of oxidation of alloys.

The anomalous change of the electric resistivity of the Ni_3Mn alloy in a magnetic field was described by Komar and Fortnyagin[457] also.

Anmanov[464], in 1949, investigated the thermomagnetic Nernst effect in crystals of ferrosilicon and of Ni_3Mn.

Regel[450] proposed a new method for the determination of electrical conductivity of metals and alloys and of rotating magnetic fields for use over a wide range of temperature, particularly in the region of solid-liquid transitions. A description of the apparatus was included. Typical determinations on indium were performed.

Smirnov(451) determined the Hall constant for ordered alloys and showed that the sign of the Hall constant may change during ordering.

B. Intermetallics and Elements of the Fifth Group of the Atomic Table

Bismuth single crystals were studied in 1940 by Davydov and Pomeranchuk(475).

Articles were written which show that the Soviets have studied superconductivity in many elements, including bismuth compounds(488). Intermetallic materials, such as Mg_3Sb_2, have been studied thoroughly for electrical properties in the U.S.S.R. Men studying these in 1948 included Zhuzo and Boltaks(492) and Kontorova(493). Others, such as Mochan(494), have studied the zinc-antimony system thoroughly, in so far as electrical properties are concerned, as a function of its chemical nature. Zhuzo, Mochan, and Ryvkin(487), also investigated photoconductivity in zinc-antimony and magnesium-antimony intermetallics.

In work by Boltaks(497), it was recognized that Mg_2Sn was intermetallic and an impurity semiconductor with a forbidden zone of 0.2 electron volt.

C. Organics

Vartanyan and Terenin(500) studied the photoconductivity of organics in 1941.

In 1947, organic luminophors were studied by Sveshnikov(503).

It was apparent from other articles that organic substances were being studied for semiconductivity, phosphorescence, etc. For example Vartanyan(504) studied phthalocyanines and anthracene.

In another article, polarized fluorescence of anthracene was discussed(506).

SECTION V

EVALUATION OF SAMPLE PUBLICATIONS

Because the abstracts of literature as collected are not always representative of the quality or complete scope of a work, several items were selected for complete translation and evaluation. These were selected on the basis of their being readily available and representative of the work of leading persons in the field of semiconductors. Specifically, the work reviewed is presented below in abstract form.

1. Work on Semiconductors, Their Applications, and, Specifically, Rectification

   a. Semiconductors and Their Applications, A. F. Joffe, Bull. Acad. Sci., U.S.S.R., 1946, Vol 10, No. 1, p 3.

This is a very scholarly review of the general theory of semiconductor characteristics including an excellent integration with immediate practical applications, as well as future possibilities. The conception is very broad with coverage of a great variety of semiconducting materials and discussion of numerous important uses, such as rectifiers, thermistors, photocells, and thermoelectric elements. It appears that the procedures outlined represent important early contributions. Joffe's interest in P-N junctions definitely predates an article on such studies published in 1947 by the Purdue group in the U. S.

Several significant characteristics are noted in the article. The first is an apparent reticence toward referring to works by foreign investigators. The second is a tendency to correlate theoretical progress

with advances in practical application. Examples are given of several cases of superior rectifier performance.

In summary, the article indicates great interest in semiconductor properties, completely adequate technical knowledge and experimental facilities, and an acute interest in the use of the scientific developments for practical applications.

This article is thought to be of such importance that a complete translation is included in Appendix I.

b. Electrical Resistance of the Contact Between a Semiconductor and a Metal, A. V. Joffe, J. Phys., U.S.S.R., 1946, Vol 10, No. 1, pp 49-60.

The experiments described represent a careful and thorough investigation of the problem. The investigator is especially to be commended for his persistent attention and evaluation of secondary effects which might lead to incorrect interpretation of the data. He appears unusually adept at taking cognizance of possible sources of errors and at reducing them by special techniques, as well as by the usual procedure of variation of parameters and comparison of results. The extent and variety of the measurements are quite large. This fact, coupled with the care which seems inherent in the work, indicates the investigation to be of monumental significance. In scope and in precision, the work appears to be of a stature equivalent or superior to the most important experimental determinations in the semiconductor field reported in American journals of similar date.

Such facts as (1) that high values of resistivity could be measured over a range of temperatures down to the liquid-air point, (2) that

additional characteristics, such as contact potentials, thermoelectric-power probe measurements, and rectification characteristics, were determined, and (3) that a great variety of electrode materials and forming techniques were studied all indicate the existence of excellent laboratory equipment at the Physico-Technical Institute. In addition, the breadth and apparent precision of the measurements suggest that in 1945 conditions must have been conducive to good research.

c. Rectification on the Boundary of Two Semiconductors, A. V. Joffe, J. Tech. Phys., U.S.S.R., December, 1948, Vol 18, No. 12, pp 1498-1510.

Results of extensive measurements on rectifying properties of numerous semiconducting materials were reviewed. Such a voluminous investigation is essentially of value from a survey standpoint. It reflects interest not only in rectification theory, as is suggested by the title and portions of the text, but more directly in the discovery of better semiconductor rectifying materials. This comment follows from the nature of the experimental attack. A program to assist theoretical analysis would involve more intrinsic studies on fewer specimens. It would necessitate, for example, knowledge of the impurity status of the materials being studied. Such information is conspicuously absent. The author does mention, however, that more detailed studies involving changes in capacity of boundary layers, as well as frequency, voltage, and temperature, are in progress.

It is interesting to note that, as a result of promising experimental observations, considerable interest is expressed in rectification by junctions of P- and N-type semiconductors. Some of the earlier work

published on P-N junctions in the U. S. predates this report by a year. For example, an article by the Purdue group in the U. S. was published in 1947. Nevertheless, the work reported by Joffe appears to be quite original and of wide general usefulness. Another pertinent fact is that interest in P-N junctions was expressed in a general paper on Semiconductors and Their Applications, published by A. F. Joffe in 1946.

2. Work on High-Dielectric-Constant Materials

a. High Dielectric Constant Materials, B. Vul, J. Phys., U.S.S.R., 1946, Vol 10, No. 2, pp 95-105.

The author reviewed the results of what was apparently a very thorough experimental investigation of certain high-dielectric-constant materials. In addition to temperature, pressure, field strength, and hysteresis measurements on the dielectric materials, associated studies were also made on crystal structure and lattice constants, effect of cation substitutions, etc. Values of specific heat near the Curie point were measured for barium titanate in order that certain thermodynamic relations could be developed. Attention was also paid to practical aspects, and there was pointed out the need in the radio industry for substances with high dielectric constants or with constants which vary in a prescribed way. The statement was made that, since it was verified that the temperature coefficient of the dielectric constant of a mixture is given by the weighted arithmetic mean, the technique is available for compounding a material of prescribed temperature-variation properties.

In summary, the investigation appears to be of high caliber, with a thorough coverage. The scope is broad, including not only a variety of experimental details and data, with associated theoretical significance, but also connections with points of practical concern.

b. <u>Dielectric Constant of Barium Titanate at Low Temperatures</u>, B. Vul, <u>J. Phys., U.S.S.R.</u>, 1946, Vol 10, No. 1, pp 64-66.

The article indicates the employment of careful and precise experimental techniques, and the existence of excellent low-temperature facilities at the Lebedev Physical Institute. The investigator took into account such corrections as connecting lead capacities and edge effects. The correlation of the dielectric constants with particle polarizabilities was discussed. One point of uncertainty, however, pervades the work. This results from the fact that the dielectric constant of barium titanate is field dependent. Vul states that "at high frequencies of several volts, ϵ is practically independent of the field strength". Measurements were apparently taken in this region. Further discussion of this point would be in order. The experimental investigation, however, appears to be of high caliber.

c. <u>Dielectric Properties of Ferroelectric Crystals and Barium Titanate</u>, V. Ginzburg, <u>J. Phys., U.S.S.R.</u>, 1946, Vol 10, No. 2, pp 107-114.

This article presents a very informative discussion on the correlation of experimental observations on ferroelectric crystals and barium

titanate, with thermodynamic considerations based on the macroscopic domain model. It is obvious that the author is quite well versed in this field. His knowledge of significant contributions to the subject is revealed by the relatively large number of references, many of them by foreign investigators. Although it seems logical that a completely satisfactory analysis must take into account microscopic characteristics, together with the theory of cooperative phenomena, it is remarkable what success the investigator has had in reproducing certain of the experimental values by means of the application of thermodynamics to the domain model. The article definitely has the appearance of a first-rate scientific paper.

3. Photoelectric Effects, Particularly in Selenium, Sulfides, and Selenides

a. Determining the Sign of the Photoelectric Current Carriers, V. P. Zhuze and S. M. Ryvkin, C. R. Acad. Sci., U.S.S.R., 1948, Vol 62, No. 1, pp 55-58.

Determination of the Sign of the Carriers of Photoelectric Current by the Condenser Method, K. K. Putseiko, Dokl. Akad. Nauk S.S.S.R., 1949, Vol 67, No. 6, pp 1009-1012.

The development of the condenser method for determining the sign of the charge carriers in photoconducting media represents a distinct achievement and valuable contribution to the experimental techniques for semiconductor analysis. The articles listed above, together with a more complete presentation by Ryvkin, including a first-order theoretical analysis of the nonstationary processes involved, appear to be of high caliber and imply a proficiency equivalent to that of the typical British or American

investigator in this field. There is present in the articles above, however, a secondary detail which indicates a certain naive attitude assumed by the authors toward semiconductor characteristics.

The illustration of this point is a table where semiconductors are tabulated in terms of chemical formulas and the observed sign of the carriers. Since it is known that the characteristics of many semiconductors are very sensitive to extremely minute impurity concentrations or crystallographic flaws, a simple characterization of the type mentioned above is now known to be completely superficial. Such classifications are, however, reminiscent of earlier German publications.

In as much as the value of the contribution is the perfection of an experimental technique useful in semiconductor analysis, the criticism cited above is somewhat parenthetical; it is not intended to detract from the importance of the work. The condenser method involves phenomena somewhat similar to those encountered in the carrier-injection experiments carried out at the Bell Telephone Laboratories and reported in 1949, somewhat later than the articles discussed here.

b. "Valve" Photoeffect in Selenium With Additions of Cadmium, B. T. Kolomietz and E. K. Putseiko, J. Exptl. Theoret. Phys., U.S.S.R., 1947, Vol 17, pp 618-873.

The discussion set forth indicates considerable experience by those investigators in the field of photoconducting materials. The experiments seem to have been carefully carried out, and the men appear to have taken careful cognizance of pertinent work done elsewhere. There are,

for example, numerous references to work carried out in Germany. It is mentioned that the influences of additions on the spectral properties of selenium photoelements are of importance, not only from the theoretical point of view, but also from a practical one, because they might help to increase the coefficient of efficiency of the photoelements. The authors point to the discovery, during the course of the experiments, of a new type of photoelement having properties which they indicate may be of valuable practical significance. It is characterized by the fact that the sign of the photocurrent depends on the wavelength of the incident light. For blue-green illumination, conduction is of the N type; for red light, it is of the P type. The investigators suggest that the techniques of compounding two semiconducting materials to produce this type of behavior may be of value in the development of methods of differential measuring of color temperatures, absorption, etc.

c. Photo-Electrical Properties of Indium Sulfide and Selenide, B. T. Kolomietz and S. M. Ryvkin, J. Tech. Phys., U.S.S.R., 1947, Vol 17, No. 9, pp 987-992.

The article indicates the existence of established techniques for studying photoconductive properties of materials. This confirms other evidence showing considerable interest in photocell development possibilities. In spite of the fact that the investigators could not theoretically account for the observed results, it seems that the experimental studies are quite noteworthy. Of particular interest are the results where an indium sulfide layer was treated with selenium, and likewise an indium selenide layer was treated with sulfur.

It would seem that particular investigation ought to have been made of the purity of the specimens, that is, an effort should have been made to ascertain the effect of minute impurities, including oxygen. However, it is admitted that the investigation, as made, offers much information for consideration.

4. Thermoproperties of Conductors and Semiconductors

a. Thermoelectric Properties of Conductors, I. L. Gurevich, J. Phys., U.S.S.R., 1946, Vol 10, No. 1, pp 67-80.

The author carried out quite an involved theoretical development in which he solved the Boltzmann equation for the perturbed distribution functions, taking into account the influence of phonon-electron interaction under a temperature gradient upon the expressions for the collision terms. Equations are derived for thermoelectric power and thermal conductivity, and the Wiedemann-Franz law is discussed.

The work represents quite an ambitious theoretical undertaking and calls for considerable knowledge in theoretical physics. Unfortunately, however, the author does not at any place take time to discuss the assumptions underlying his developments. Even at the end of the article, there is hardly more than a trivial discussion of the relative importance of the correction terms. One additional disconcerting factor is the complete absence of any reference to other work. This makes it difficult to assess the relative ratio of originality and sheer persistence in Gurevich's work. The point is especially pertinent since considerable work has been done

in Germany and in England in the 1930's on electron-phonon interactions below the Debye temperature.

b. Thermionic Emission From Thin Semiconductor Films, K. B. Tolpygo, J. Tech. Phys., U.S.S.R., 1949, Vol 19, No. 11, pp 1301-1311.

The author attempted to investigate the characteristics of emission from a semiconductor surface when the semiconducting material is reduced to a very thin film on a metal base. His procedure is to consider a perfectly flat model of a surface with discretely defined regions of contact, and then apply the equations for equilibrium contact conditions as developed by Davydov and others. The problem is reduced to a succession of algebraic jugglings upon which it is necessary to make further assumptions in order to arrive at results amenable to discussion. When it is recalled that recent investigations of surface phenomena have indicated the importance of considering such details as surface effects, electron wave properties and reflection conditions, image potential for noncontinuous media, etc., it may be expected that much agreement between Tolpygo's results and actual fact would be quite fortuitous. Unfortunately, however, the question of the existence of such a possibility is not resolved, since the author gives only a rather general qualitative discussion of the correlation of his results with experimental data.

In summary, it would appear that the author has been somewhat too anxious to publish.

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5. Chemical Work

Rate of the Reaction Between H_2S and Certain Metal Oxides, A. L. Potinyan, J. Appl. Chem., U.S.S.R., 1948, Vol 21, No. 8, pp 807-809.

The author had success in explaining the inhibition with time of the reaction rate between H_2S and certain oxides by a diffusion mechanism of the H_2S through a porous crust of reactant products formed on the small grains of the oxide material. His results fit very well the experimental data obtained by other investigators and reported in the journal for the previous year. Although the analysis was exceptionally straightforward, this simplicity does not detract from the commendation due the investigator. It is a small, but important, job well done.

From the above, it will be noted that the items considered by no means represent the entire scope of the work in progress or of the leading personalities doing it. In general, it can be said that the work reviewed shows a competence and originality comparable to work in similar fields carried out anywhere else in the world. However, when it is considered that the recognized realm for marked advance in semiconductors is the control of imperfections and defect configurations, it is evident that the Soviet studies are lagging behind those presented in U. S. and British journals.

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SECTION VI

PERSONALITIES, THEIR SPECIALTIES, AND THEIR LOCATIONS AND PATENT CONSIDERATIONS.

As was pointed out in Section I, the yardstick for determining the status of the capability of the Soviet Union in solid-state electrical-device research involves ways of estimating not only the quality and the nature of the research work (see Section IV) and the number of written articles (as discussed in Section III), but also the number of people, types and amounts of equipment, and patent information. This section presents information regarding the latter group of factors with the exception of patents.

Apparently, there are no patents in the U.S.S.R. The Government, however, has a set of engineering standards which may be analogous to patents. None of these were obtained. However, it was found, too late for inclusion in this report, that they could have been obtained from the Library of Congress. It is believed that, in those areas where classified literature is predicted or expected, the engineering standards might reveal the desired information; this is on the basis of the assumption that the same security regulations are not placed on engineering standards as on open literature.

When the Bibliography was compiled, cursory inspection supported the assumption that, in general, major scientists publish papers more often than do other scientists. This led to a listing, shown in Exhibit A of this section, of all authors who had written at least three papers during the period studied. This number of papers was arbitrarily chosen so as

to include the names of men who might be in a younger group, from which future leaders will develop. Exhibit A forms a "watch list" of personalities; it could also give clues as to the type of work going on where these persons are located, since their specialties are at least partially established.

The above listing was then regrouped according to specialties in order to locate personnel active in major fields of effort, as shown in Exhibit B of this section. This grouping by fields and comments on outstanding personalities in each field are discussed below.

1. Theory and Semiconductors - General

Perhaps one of the most important men in this category is J. Frenkel, who is located at the Leningrad Physico-Technical Institute. This evaluation is made in consideration of the fact that Frenkel has written a large number of papers over the period 1941-1951, covering almost the entire field of semiconductors. He has also worked with many junior personalities. These observations indicate consistency of effort, versatility in the field, and ability to teach and lead younger men.

S. Pekar's work is of very good quality. It is slightly narrower in scope than Frenkel's but includes his famous theory of polarons. He is listed among personnel at the Institute for Physical Problems, Moscow.

The work of A. F. Joffe, while of great import, was produced before 1943. At this time, he began work of an experimental nature with A. V. Joffe. He is reputed to be a very fine organizer, administrator, and leader, and has taken on administrative responsibilities as Director of the

Leningrad Physico-Technical Institute. A. F. Joffe is a member of the Presidium of the Academy of Sciences, Director of the Department of Physico-Mathematical Sciences, and Chairman of the Commission on the Problems of the Atomic Nucleus. Apparently, his efforts in recent years have been in the Soviet atomic program.

B. I. Davydov's writings cover all aspects of semiconductors, but no publications have been recorded since 1943.

I. L. Gurevich considered magnetic effects and photoconductivity between 1945-1950.

Volkenshtein has written articles having fairly wide coverage and has been associated with Bonch-Bruevich and Komar. The former has been active in the semiconductor field but has published little during the period studied, while the latter has written extensively between 194[illegible]-1948 on alloys and magnetic effects.

Morgulis and Gubanov seem to be relatively new to the semiconductor field, and their future works may prove interesting.

2. Rectifiers (Cu_2O, Se, etc.)

This field has not been worked extensively by the Soviets since about 1947-1948, according to open literature. Men of importance in this field include Nasledov, who published between 19[illegible]1-194[illegible]; [illegible], between 1940-1947; and [illegible], between 1936-[illegible]. Although [illegible]'s work was early and falls outside the time limits of this study, he was supposedly located at the Leningrad Physico-Technical Institute in 19[illegible]. Persons such as Lyashenko, Pavlenko, Boltaks, Nekrashevich, and Shifrin are known to

be associated with the rectifier field, but their publications during the period studied did not show them to be interested solely in rectifiers.

3. Photoeffects

Lashkarev appears to be one of the leading men in this field, being active between 1941-1950. His works cover many aspects of photoconductivity, especially with respect to copper oxide. Lashkarev is located at the Ukrainian Academy of Sciences, Kiev.

Kolomiets published during 1947-1951. His major work has been in photoelectric effects, especially photoresistances, in a variety of materials which include Se, S-Th, BiS, and PbS.

Ryvkin has written during 1948-1951. His works include studies of Cu_2O and intermetallic compounds.

4. Luminescence and Phosphors

Antonov-Romanovskii has written extensively during 1942-1950. His subject matter borders on the theoretical, yet encompasses solely phosphors and luminescence. He published alone through 1947, but his work since then has been in conjunction with others. He is located at the Lebedev Institute, as are two of his co-workers, Adirovich and Anikina, with whom he was associated in 1946 and 1950, respectively.

Other personalities of note in this field include Levshin, who is a member of the Scientific Council, Lebedev Physical Institute, Moscow, and published during 1941-1951, and Shalimova, who appears during 1948-1951. Tolstoi's name appears on seven papers during 1949-1950, and, in

most cases, he is junior author. This may indicate either that he is a good experimentalist or that he is not capable of leading research.

5. Dielectrics

One of the outstanding men in this field is Vul. His works during 1944-1946 are mainly concerned with barium titanate, on which he was a pioneer. He is of sufficient importance to have a laboratory named for him in the Lebedev Physical Institute, of which he is a Scientific Council member. Vul is also Secretary of Personnel (since 1949) of the Department of Physico-Mathematical Sciences. He also has associated with Ginzburg and Goldman, both men of promise.

Skanavi has written during the years 1944-1951, covering broadly the field of dielectrics. He was associated with Vul in the early stages of the work on barium titanate and since, has associated with such scientists as Tolstoi, Feofilov, and Lebedeva. He is located in Vul's laboratory at the Lebedev Physical Institute.

Renne's studies between 1940 and 1950 included important work on capacitors.

Other men of importance in this field include Gutin, known for his work on electrolytic capacitors, and the versatile Pomeranchuk.

6. Alloys - Intermetallic Compounds, Magnetic Effects

This aspect of solid-state physics borders on that of semiconductors in that some intermetallic materials exhibit semiconductor properties and that magnetic-field effects are of interest.

Workers of importance in this field include Boltaks, Galperin, and Vonsovskii.

7. Physical Chemistry and Germanium Chemistry

Kapustinskii has done work on ionic crystals and sixth-group elements.

Ivanov-Emin has done work in this field on germanium chemistry, which may belie the apparent lack of Soviet interest in germanium.

8. Miscellaneous Materials

Probably the outstanding man here is Zhdanov. His works include papers on selenium and X-ray crystal-study techniques. He has worked with Minorvina and Smirnov. Zhdanov is a member of the Commission on Roentgenography, an independent commission of the Department of Physics and Mathematical Sciences, and Departmental Chairman and Science Council Member of the Institute of Crystallography.

The comments as listed above are brief and intended to highlight only the outstanding personalities. More complete analyses of the specialties of all persons associated with the particular fields listed are presented in Exhibit B.

EXHIBIT A

ALPHABETICAL LISTING OF PERSONS PUBLISHING AT LEAST THREE ARTICLES DURING THE PERIOD 1940-1951

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EXHIBIT B

LISTING OF IMPORTANT SOVIET PERSONALITIES
ACCORDING TO THEIR
SPECIALTIES IN SEMICONDUCTOR RESEARCH

1. Theory and Semiconductors - General

B. I. Davydov has considered all aspects of semiconductors. In 1940, he associated with I. Pomeranchuk to study problems concerning electrical properties of transition metals at low temperatures; he also worked with I. Schmushkevitch on strong electric-field effects on semiconductors. In 1943, he collaborated with B. B. Gurovich to study electrical properties of semiconductors. He published eight papers between the years 1939-1943.

J. Frenkel studied the effects of impurities on semiconductors, dielectrics, magneto-optical effect, oxide films, magnetic resonance in solids, crystalline bodies (flow and surface tension), crystals, and electric contacts between metals. He associated with Kontorova in 1943 on work concerning crystals and statistics; with Gindin, Moroz, Putilova, and Shpanskaya in 1950 on a study of dielectrics; and with Gindin, Moroz, and Putilova in 1951 in studying semiconductors and dielectrics. Frenkel is apparently a leading man in this field in the U.S.S.R. He published 11 papers between the years 1941-1951.

A. I. Gubanov discussed types of conductivity and theory of semiconductors in the three papers he published in 1950 and [illegible]. He appears to be a new man.

D. B. Gurevich associated with Tolstoi in 1950 to study photoconductivity; with Tolstoi and Feofilov in 1949 and 1950 to work on luminescence of semiconductors, specifically the photoconductors Bi_2S_3 and CdS; and with Davydov in 1943. He published six times in the years 1945-1950.

I. L. Gurevich worked on thermoelectric, thermomagnetic and galvanomagnetic properties, and conduction and photoconductivity of [illegible]. He published four times in 1945-46.

A. F. Joffe wrote reviews of semiconductors; he associated with A. V. Joffe in 1940 and 1941 to study effects of high electric fields on semiconductors, metal-to-semiconductor contacts, and rectification. He wrote six papers in the years 1940-1943.

A. Komar has studied the electric and magnetic effects of the alloys $AuCu_3$ and Ni_3Mn. He associated with Portnyagin in 1948 to study electric and magnetic effects of the alloys Cu_2Pd and Ni_3Mn; with Volkonshtein in 1948 on the subjects of ferromagnetism and the Hall constant; and with Sidorov in 1941 to study the Hall constant and atomic arrangements of the alloy $AuCu_3$. He produced nine papers from 1940 to 1948.

N. D. Morgulis has worked on semiconductor cathodes and the photo and optical properties of Sb-Cs cathodes, once in collaboration with Borzyak. He is another postwar writer and produced four papers between 1946-1948.

S. Pekar worked on the theory of contacts to semiconductors, electron effects, and crystals; he developed a theory of polarons (one of his most famous works). He associated with Tomasevich in 1947 to study thin semiconducting layers and thermoelectronic emission; with Landau

in 1948 to consider the polaron theory; and with Perlin in 1950. He has turned out 10 works, one in 1941 and the remainder between 1946 and 1950.

F. Volkenshtein has studied the electrical properties, photo-electric properties, and theory of semiconductors. He associated with Komar in 1948 to study the Hall constant of ferromagnetic metals; with Bonch-Bruevich in 1950 to study the Theory of Electric Behavior of Ionic Crystals. He published five times, once in 1941 and the remainder during the period 1948 to 1950.

2. Rectifiers (Cu_2O, Se, etc.)

K. V. Astakhov studied the electrical properties of selenium and selenium rectifiers and impurities in selenium; he associated with [illegible] in 1945 and 1946 and with [illegible] and Kotkina in 1946 to study electrical properties of selenium and selenium rectifiers and the physical properties of liquid selenium. He wrote four papers during 1945-1947.

Yu. A. Dunaev studied Cu_2O rectifiers and has done temperature work on PbS. He associated with Kurchatov in 1940 in studying sulfide rectifiers; with Levinson and Tuchkevich in 1941 to work on selenium rectifiers and electrode metals and materials; and with Maslakovets in 1947 on the physical properties of PbS. He published six times between 194[illegible] and 1947.

A. V. Joffe has done work on electrical properties of contacts in rectification and has worked in conjunction with A. F. Joffe. He published four papers between 1940-1948.

E. K. Kalyshev has worked on selenium rectifiers and studied the electrical properties of selenium. He associated with Nasledov in 1943 on selenium work, and with Kortener in 1941 and 1943 in work on the subjects of selenium and thermal conductivity of selenium. He wrote three papers between 1941 and 1943.

D. Nasledov studied the electrical properties and photoconductivity of selenium and worked on selenium rectifiers. He associated with Kozlovskii in 1943 in studying the electrical properties of selenium and the effects of Sb and Te on Se; with Kurashov in 1945 in studying the electrical properties and thermal effects in semiconductors; and with Malyshov in 1943 in studying the effect of low temperatures on selenium rectifiers. He has written eight papers over the years 1941-1945.

P. V. Sharavskii has studied the temperature and pressure effects of Cu_2O and selenium rectifiers. In 1940 he associated with Manovskii to study temperature compensation in Cu_2O rectifiers; with Marchenko to study the electrical properties of Cu_2O rectifiers; and with Kraus to study the d-c and a-c electric breakdown in Cu_2O rectifiers. He wrote six papers during the period 1936-1940.

3. Photoeffects

B. A. Burshchevskii studied photoeffects of Sb-Cs cells and silver halide compounds, and photoeffect and light absorption in silver halides. He wrote three papers between 1947 and 1949.

N. S. Khlebnikov has studied the electrical effects and chemical compositions of photoelements and Sb-Cs cells. He associated with Mel and

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in 1945 and 1948 to study energy levels in Sb-Cs photocells. He published five papers between 1940 and 1950.

B. T. Kolomiets has worked on the photoelectric effects of Se and Tl_2S cells, and on the photoresistive materials Bi and PbS. In 1947, he associated with Putseiko to study photoeffects in Se and with Ryvkin on the photoeffects of InS and InSe. He joined Sheftel in 1951 to study thermistors. He wrote seven papers between 1947 and 1951.

V. Lashkarev has made photoconductivity, barrier-layer, and diffusion studies. He associated with Kosonogova in 1941 and 1948 in studying photoconductivity and rectification in Cu_2O; with Fotagenko in 1949 on photoconductivity and kinetics studies; with Fedorus in 1949 to study photoconductivity in Cu_2O; and with Fedorus and Fotagenko in a similar study on PbS. He wrote 11 papers in the period 1941-1950.

E. K. Putseiko studied photoelectric effects in thallium halides. He associated with Reiklyar in 1950 in studying photoeffects in silver halides; with Terenin in 1950 in studying electrical effects of organic dyes on semiconductors. He wrote five papers between 1949-1951.

S. M. Ryvkin studied photo-emf in Cu_2O. He associated with Zhuze in 1948, 1949, and 1951 in studying photoconductivity in Cu_2O and theory regarding photoconductivity; and with Zhuze and Mochan in 1948 in studying photoconductivity in intermetallic compounds. He wrote eight papers between 1949 and 1951.

A. T. Vartanyan studied anthracene as an organic semiconductor and associated with Terenin in 1941 in studying photoconductivity in organic compounds. He wrote three papers between 1941 and 1950.

in 1945 and 1948 to study energy levels in Sb-Cs photocells. He published five papers between 1940 and 1950.

__E. T. Kolomietz__ has worked on the photoelectric effects of Se and Tl_2S cells, and on the photoresistive materials Bi and [illegible]. In 1947, he associated with Putseiko to study photoeffects in Se and with Ryvkin on the photoeffects of InS and InSe. He joined Sheftel in 1951 to study thermistors. He wrote seven papers between 1947 and 1951.

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__E. K. Putseiko__ studied photoelectric effects in thallium halides. He associated with Meiklyar in 1950 in studying photoeffects in silver halides; with Terenin in 1950 in studying electrical effects of organic dyes on semiconductors. He wrote five papers between 1949-1951.

__S. M. Ryvkin__ studied photo-emf in Cu_2O. He associated with Zhuze in 1948, 1949, and 1951 in studying photoconductivity in Cu_2O and theory regarding photoconductivity; and with Zhuze and Mochan in 1948 in studying photoconductivity in intermetallic compounds. He wrote eight papers between 1948 and 1951.

__A. T. Vartanyan__ studied anthracene as an organic semiconductor and associated with Terenin in 1941 in studying photoconductivity in organic compounds. He wrote three papers between 1941 and 1950.

V. Zhuze worked on a Theory of Rectification. He associated with Starchenko in 1940 in studying electrical conductivity and thermoelectric properties of Cu_2O_3; with Mochan and Ryvkin in 1948 in studying photoconductivity in intermetallic compounds; and with Ryvkin in 1948, 1949, and 1951 to study photoconductivity and effects of light on Cu_2O. He wrote seven papers in the period 1940-1951.

4. Luminescence and Phosphors

E. I. Adirovich wrote three papers on phosphors, crystals, and luminescence between 1948-1951.

L. I. Anikina wrote three papers on phosphors, associating with Antonov-Romanovskii on two of them, during the period 1949 to 1951.

V. V. Antonov-Romanovskii studied all phases of phosphor work. He associated with Anikina in 1949 and 1950; with Epshtein in conducting experimental work on phosphors in 1949; with Krylova in doing an analysis of phosphors in 1949; and with Shchukin in doing experimental work concerning excitation and absorption on phosphors in 1950. He wrote nine papers between 1942 and 1950 and seems to be a good man to watch.

F. I. Feofilov worked on luminescence and photoconductivity with L. P. Gurevich and Tolstoi, and on theory of dielectrics with Tolstoi, [illegible], and Lebedeva. He collaborated on six papers between 1947 and 1950.

M. L. Kats studied luminescence in alkali halides and associated with Zhukova in 1948 in studying luminescence and excitation in ZnS phosphors. He wrote three papers between 1948-1949.

V. Levshin studied luminescence in ZnS-Mn phosphors and crystals and crystal phosphors. He worked with others on infrared and alkaline-earth types of phosphors in 1947, and associated with Veits in 1950 in

studying optical properties of ZnS-Mn, ZnS-Cd-Mn, and ZnS-Cu phosphors. He wrote six papers between 1941 and 1951.

M. Kil studied temperature effects on luminescence in ZnS. He associated with Ortman in 1949 in studying luminescence effects of putting Cu into ZnS and with Born and Zimmer in 1948 in studying luminescence produced by beta rays in ZnS. He wrote three papers between 1948 and 1949.

A. N. Sevchenko wrote three papers on luminescence, uranium-uranyl glasses, and crystals between 1944 and 1949.

K. V. Shalimova studied temperature effects on luminescence in KI-Th and NaI-Tl alkali halides. She also worked on spectra of absorption and emission of ZnO. She wrote five papers between 1948 and 1951.

I. Ya. Sveshnikov studied phosphorescence in organics. He associated with Dikon in 1949 to study phosphorescence in organics and with Ermolaev in 1950 to study low-temperature effects on phosphorescence of organics. He wrote three papers between 1947 and 195 .

T. V. Timofeeva studied alpha- and gamma-ray excitation, scintillation, and luminescence of ZnS. She associated with Belinskii, Akerman, and Vainberg in 1950 to study phosphate phosphors. She wrote five papers during the period 1945-1950.

N. A. Tolstoi has worked on luminescence theory and ZnS-Mn phosphors, and associated with Feofilov, B. B. Gurevich, Sasnovi, and Lebedeva, as secondary author, seven times during 1949-1950.

5. Dielectrics

V. L. Ginzburg has studied superconductors, thermoelectricity, and dielectrics (especially $BaTiO_3$) and reported in four papers between 1944 and 1949.

I. M. Goldman has worked on dielectrics, especially the titanates - chiefly $BaTiO_3$ - and associated with Vul in 1945 and 1946. He wrote three papers.

S. S. Gutin studied the temperature dependence of the Al_2O_3 electrolytic capacitor and made a study of the oxide layer on aluminum in electrolytic capacitors. He associated with Godes in 1945 on electrolytic capacitors and metal-covered fabrics for same. He wrote three papers from 1940 to 1945 and one in 1951.

M. S. Kosman studied dielectrics and associated with Sezina in 1947 to work on high-temperature effects in dielectrics; he joined with Goldshtein in 1951 to do experimental studies on barium titanate. He wrote three papers between 1947 and 1951.

I. Pomeranchuk has investigated thermal conductivity and temperature effects on dielectrics. He associated with Davydov in 194[illegible], and with Akhiezer in 1945 in studying thermal conductivity of bismuth. He wrote seven papers in the years 1941-1945.

V. T. Renne has worked on paper condensers. He associated with Broido in 1940 in studying silver contact layers on Cu_2O rectifiers and with Kh. Kh. Renne in 1945 in the development of dielectric impregnants for paper. He wrote five papers between 1940-1950.

G. I. Skanavi studied temperature effects on dielectrics, especially $BaTiO_3$. He associated with Vul in 1944 in work on ceramic capacitors and with Domoshina in 1949 to study polycrystalline dielectrics; he joined Tolstoi, Feofilov, and Lebedeva in 1949 to work on a theory of dielectrics. In 1945, he associated with Domoshina and Chrelashvili in studying temperature effects on the electric conductivity of dielectrics. He wrote seven papers in the period 1944-1951.

B. M. Vul pioneered in titanate dielectrics, especially $BaTiO_3$. He associated with Skanavi in 1944 in a study on ceramic capacitors; with Goldman in 1945 and 1946 in studying field effects on titanate dielectrics; and with Vereshchagin in 1945 to study pressure effects on $BaTiO_3$. He wrote 14 papers in the years 1944-1946.

D. Zernov studied secondary emission and electrical breakdown of thin films of dielectrics; he associated with Elinson and Levin in 1944 in studying dielectric thin films and electronic-emission problems. His four papers were written in the period 1944-1950.

6. Alloys - Intermetallic Compounds, Magnetic Effects

N. S. Akulov studied magnetostriction and magneto heating in alloys. He associated with Alizade and Belov in 1949, and Kirenskii in 1940. His three papers were written in the period 1940-1949.

R. G. Annaev studied thermoelectrical, thermomagnetic, and electrical effects in alloys. He wrote three papers during 1948-1949.

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K. P. Belov worked on ferromagnetics and associated with Akulov and Alizade in studying magnetostriction in Fe-Pt alloys in 1949. He wrote three papers during 1948-1949.

B. I. Boltaks studied electrical, thermo-, and magnetoeffects in intermetallic compounds including Mg_2Sn, and associated with Zhuze in studying the physical properties of Mg_3St_2. His four papers were published during 1948-1950.

F. Galperin studied magnetic properties of Cu-Mn alloys and the atomic physics of metals and magnetics. He associated with Perkalina in 1949 on magnetic alloys with Te. He wrote four papers between 1946 and 1951.

N. Nakhimovich studied magnetic effects in alloys and reported low-temperature studies of zinc in three papers written during 1941-1942.

I. P. Selissky studied magnetic properties in such Fe alloys as "Sendust" and also made crystal studies. He associated with Zaimovsky in 1941 on the magnetic properties of "Sendust" (Fe-Si-Al) alloys, and studied the cause of high permeability in these alloys. He published three times during 1941-1946.

S. Sidorov studied Hall effects of the alloys $PdCu_3$, $AuCu_3$, and AuCu, and worked on the atomic structure of alloys. He wrote three papers during 1946-1947, and also associated with Komar in 1941.

S. V. Vonsovskii studied ferromagnetic theory and electrical conduction in single crystals and alloys. He wrote four papers between 1946-1948.

7. Physical Chemistry and Germanium Chemistry

B. N. Ivanov-Emin worked in germanium chemistry. He associated with Alimarin in 1944 in studying germanium production using mercury cathodes, and with Kostrikin in 1947 in studying the chemistry of germanium and the alkali metals. He wrote three papers in the period 194[illegible]-1947.

A. F. Kapustinskii studied ionic crystals. He associated with Golutyin in 1947 in studying the physical chemistry of selenium, sulfur, and iodine; with Makolkin and Kirshtalik in 1947 in work on the physical chemistry of selenium, hydrogen, and sixth-group elements; and with Selivanova in 1949 in a study of the physical chemistry of lead selenate. He wrote four papers between 1947 and 1949.

A. V. Pamfilov worked on the physical chemistry of TiO and [illegible] with Fridman. He associated with Ivantscheva in 194[illegible] in a study of the physical chemistry of Ti and TiO_2. He wrote three papers during 194[illegible]-194[illegible].

F. Miscellaneous Materials

A. Akhiezer worked on the electric breakdown of crystals. He associated with Lifshits in 1940 and with Pomeranchuk. He wrote three papers between 1940 and 1945.

G. V. Akimov studied electrical analysis techniques and associated with Paleolog in 1946 on the electrochemistry of protective films. He wrote three papers in 1946.

E. V. Gorelik studied contact potential and electron emission of oxides. He associated with Dmitriev in 1948 in a study of the conductivity in high electric fields of dielectrics. He wrote three papers during the period 1945-1948.

Z. V. Minervina made an X-ray investigation of the crystal structure of silicon carbide. She associated with Zhdanov in 1945 and 1946 on this study and with Zhdanov and Nevzorova in 1948 on similar studies. She wrote five papers between 1945 and 1948.

G. S. Zhdanov worked with selenium. He joined Smirnov and Breger in 1944 to study the physical chemistry of CdI_2. He associated with Scharvin in 1945 in a study of selenium; with Minervina in 1945 and 1946 on the X-ray crystal studies of silicon carbide and continued this study with Minervina and Nevzorova in 1948. He wrote seven papers in the years from 1945 to 1948.

APPENDIX I

TRANSLATIONS OF SIGNIFICANT ARTICLES

1. Zhurnal Eksperimentalnoi i Teoreticheskoi Fiziki, May, 1940, Vol 10, No. 5, pp 576-580

SCIENCE CHRONICLE:

THE LENINGRAD PHYSICO-TECHNICAL INSTITUTE OF THE ACADEMY OF SCIENCES, U.S.S.R.

M. S. Scminsky

The Leningrad Physico-Technical Institute (LFTI) was established 18 October 1918. In 1940, Academician A. F. Joffe had been its Director for more than 20 years.

The program of the Institute has been continuously widened since the start of its activity and has been covering ever-new fields of science and engineering, which necessitated an increase of scientific personnel and conversions of whole departments into independent research centers. The Leningrad Physico-Technical Institute became the source of many specialized physical and physico-technical institutes and created many schools of physicists.

Until mid-1936, LFTI was in the Narkommash (The People's Commissariat for Machine Building). In June, 1939, Sovnarkom decided to transfer the Institute from Narkommash to the Academy of Sciences, U.S.S.R.

At the present time, LFTI has three basic groups: (1) electrophysics, (2) nuclear physics, and (3) molecular physics. Seventeen laboratories belong to these groups.

The following article will mention only the most prominent results obtained during the year 1939.

I. The Electrophysics Group

Group Head: Academician A. F. Joffe

The main problem of determining the electrical properties of solids is at present centered on semiconductors which are finding wider and wider application in modern electrical engineering. Many laboratories of LFTI are devoting their efforts to this problem.

1. Semiconductor Laboratory

Laboratory Head: Academician A. F. Joffe

This laboratory conducted and completed research on the behavior of semiconductors in strong electric fields, for it is under such conditions that semiconductors find their application. It was established that electric conductivity increases in a strong field and depends on neither the number of initial electrons nor an increase in their mobility; tests proved that the increase of electric conductivity in strong fields is due to an increase of charge carriers. Basic laws governing currents in strong fields were established and a critical analysis of current representations and theories was published during 1939 in the ZhTF (Zhurnal Tekhnicheskoi Fiziki).

Investigations of 220 combinations of two semiconductors connected in series led us to the fact that the deviation from Ohm's law must be

related to the rectifying effect of semiconductors. All semiconductors studied could be placed in a certain series such that any member of the series performs rectification of one sign with every succeeding member and rectification of the opposite sign with every preceding member. The Laboratory subjected to experimental tests B. I. Davydov's rectification theory, which considers the equilibrium of a semiconductor with a metal possessing different contact potential; the relation, expected by B. I. Davydov, with the contact potential was not observed.

2. Cuprous Oxide Rectifiers Laboratory

Laboratory Head: Candidate of Physico-Mathematical Sciences, P. V. Sharavskii

The production of big rectangular plates of sizes 40 x 130 mm and 80 x 20 mm was first completely organized by the Laboratory and then transferred to industry. The following problems were solved:

(1) The effect of surface treatment of copper upon the properties of cuprous oxide rectifiers

(2) The computation of the data for big cuprous oxide plates operating under artificial air cooling

(3) The test operation of rectifiers within a wide temperature range

(4) The design and construction of a light-duty rectifier of 12 volts - 6 amperes and 24 volts - 1 ampere

(5) The design and construction of a 40-volt - 5-ampere rectifier.

The experimental data obtained by the Laboratory furnished the basis for the technical design of a rectifier of 1,500 amperes - 6 and 12 volts, executed by the designing organization "Metallokhimiashchita", in order to equip a galvanizing plant.

The Kharkov electromechanical and turbogenerator plants started the production of some rectifier types that are based on methods developed by the Laboratory.

Besides direct experimental work, the Laboratory has been active also in organization and consultation work on problems of rectification. Only last year 54 consultations were held with plants and institutes.

3. New-Type Rectifiers Laboratory

Laboratory Head: Candidate of Physico-Mathematical Sciences, B. V. Kurchatov

Work on new types of hard rectifiers was conducted along two lines:

(1) Completion of the study of copper sulfide and magnesium
(2) Search for new semiconducting materials for use as rectifiers.

It is known that the contact of copper sulfide and magnesium permits rectification of currents as strong as 7 amperes in an area of only a square millimeter. In 1938, the Laboratory accepted this problem and solved it by constructing a copper sulfide and magnesium rectifier with a wide operating area as large as 4 cm^2, which permits rectification of currents as large as 50 to 100 amperes by a single element.

In 1939, the Laboratory successfully eliminated a basic defect of the rectifier, namely, its rapid aging, and achieved great stability of operation. Finally, the first technical model of a rectifier of 5 volts - 60 amperes was built. The new rectifier is distinguished by extremely small dimensions and possesses great mechanical strength.

In its present stage the rectifier may be used in electrolysis and is also being used for lighting in motion-picture equipment.

4. Selenium Rectifiers Laboratory

Laboratory Head: A. Z. Levinson

A technological process for the purification of selenium used in rectifiers has been developed. It was established that rectifiers made from pure selenium without admixtures have electric parameters that are no poorer than those of German samples. It was proved that domestic selenium is appropriate for selenium rectifiers if purified according to the method developed by the Laboratory. A selenium rectifier of 110 volts - 0.3 ampere was produced.

5. Photocells Laboratory

Laboratory Head: Candidate of Physico-Mathematical Sciences, Yu. P. Maslakovets

The main problem of the Laboratory consisted of improving further the thallous sulfide photocells made by the Institute in 1938 and used in practical applications. The Laboratory performed much work along these two lines of theory and practice.

At present, the most important consumer of photocells in the U.S.S.R. is the motion-picture industry, which, until recently, used only gas-filled photocells with external photoeffect. In this respect, much work was done together with the factory "Kinap" (Kinema apparatus) on the possible application of photocells with a blocking layer of thallous sulfide for use in sound-reproducing equipment. It should be noted that great specialists in this matter considered as impossible the application of thallous sulfide photocells in motion pictures.

In cooperation with the plant "Kinap", the laboratory designed a special amplifier for operation with the new photocell. Such equipment was installed experimentally in one of the motion-picture theaters in Leningrad. The results of a ten-month test showed: (1) the full possibility of application, in sound movies, of thallous sulfide photocells with a blocking layer; and (2) that the thallous sulfide photocell has many advantages in comparison with the usual photocells with external photoeffect, namely, its application conspicuously reduces external noises and eliminates the need for additional amplification. These properties of the new photocells improved the quality of the sound and facilitated operation so much that the movie theater in which the experimentation was performed changed entirely to thallous sulfide photocells in July, 1939.

At the present time, three amplifier units with thallous sulfide photocells produced by the plant "Kinap" are installed for commercial use in three movie theaters in Leningrad. Negotiations are under way for the plant to produce a thousand of such units. The new photocell possesses great spectral sensitivity, with a maximum around 1,000 millimicrons and also

great integral sensitivity, as high as 8,000 μ A/lumen. Thus, it can be used not only in the motion-picture industry but also in many other fields; for example, the new photocell has already found application in the mining industry for the indication of gases.

It is necessary to note that the production of new photocells, as well as of new rectifiers, is based on extensive studies in the physics of semiconductors. These studies became possible only when the quantum mechanical theory became applicable to practical problems.

<u>6. Laboratory of High-Voltage Techniques</u>

<u>Laboratory Head</u>: <u>Doctor of Physico-Mathematical Sciences, B. M. Gokhberg</u>

In 1939, the high-voltage laboratory conducted work along three lines:

(1) Research on dielectric gases and their possible practical application

(2) Tests on a 700-kv electrostatic generator

(3) The use of thin poor-conducting layers for potential distribution on the surface of insulators in order to eliminate surface discharge.

<u>a. Research on Dielectric Gases</u>. In the research on the physical properties of dielectric gases, the LFTI considered the problem of comparing such constants as the ionization excitation potentials and temperature of electrons in gaseous plasma with the dielectric constants of gases that

possess high and low insulating power. This research has been fully completed.

Difficulties arose in the application of dielectric gases, due to their unsuitable physical and chemical properties.

A gas without these deficiencies was found and given the name of "elegas". Having a dielectric constant 2.2 times greater than air, this gas is chemically inert and at ordinary temperatures does not liquefy under high pressures. Tests performed with various pressures up to 10 atmospheres proved that the breakdown voltage is 700 kv/cm at 10 atmospheres.

In 1939, tests were performed, in cooperation with the plant "Sovkab__"*, on the use of "elegas" in gas-filled cables. Tests on a segment of cable gave positive results. Recently the SNK (Council of the People's Commissariat) decided that during 1940 equipment should be built for the production of gas to be used in gas-filled cables under pressure.

b. Improvement and Tests of a 700-kv Electrostatic Generator.

In 1938, a multidisc "elegas"-filled electric generator was constructed with potentials up to 700 kv and with a cathode-ray tube.

Tests on the generator, performed in 1939, at excess pressure of 2.5 atmospheres gave satisfactory results. At this pressure, a potential of 300 kv was obtained which approximately corresponded to the theoretically computed value in the specifications. Therefore, there is every reason to assume that the generator will develop the planned potential of 700 kv in an atmosphere of compressed "elegas".

*The complete name of the plant was not legible.

II. The Nuclear Physics Group

1. Beta Decay Laboratory

Laboratory Head: Corresponding Member of the Academy of Sciences, U.S.S.R., A. I. Alikhanov

Work in the Laboratory was performed along the following lines:

(1) Specification and final elaboratoration of results previously obtained in the Laboratory

(2) Finding new methods for solving problems of beta decay and cosmic rays.

The first problem is connected with the following items: (1) research at the end of the spectrum by the double-spectrographic method, and (2) the scattering of relativistic electrons.

The first work finally established that within the limits of the present theory of decay the neutrino's mass cannot be set equal to zero. In the second work, investigating the scattering of high-energy electrons for wide angles, it was found that the scattering of electrons obeys the laws of quantum mechanics, with only the usual Coulomb forces being taken into consideration; specific nuclear forces do not appear in this case. In particular, the second work included: (1) the development of methods for observing the recoil of atoms during beta decay and capture of orbital electrons, (2) the development of methods for observing and investigating the ionizing component of cosmic rays, and (3) the development of methods for observing electron absorption in an elementary action, and many other works.

The first work attempted to clarify by direct tests the existence of the neutrino and measure its mass. A method was developed for studying the recoil of heavy atoms during beta decay.

The purpose of the second work was to construct a system of Geiger-Mueller counters and tube amplifiers so that a study, separate and independent of the ionizing particles, could be made of the composition and properties of cosmic rays. After many great difficulties had been overcome and after many tests of counters and amplifiers, such a system was finally constructed.

The third work evolved methods closely approaching the second one and also met great difficulties which cannot, as yet, be considered as completely overcome.

2. Nuclear Physics Laboratory

Laboratory Head: Doctor of Physico-Mathematical Sciences, I. V. Kurchatov

In 1938, LFTI discovered soft electron radiation associated with isomeric transmutation of bromine. This radiation was ascribed to internal conversion which occurs upon transition of the isomeric metastable nucleus into its ground state.

In 1939, the following two problems were proposed: (1) to justify experimentally the hypothesis that the soft radiation of bromine originates in conversion, and (2) to study the mechanism governing radioactive transmutations in the case of nuclear isomerism of bromine, making use of the new fact of conversion radiation.

In order to compare nuclear isomerism with experience, tests were made to determine the coefficient of internal conversion during isomeric transmutations of bromine and to study the relative probability of conversion on K and L levels of bromine. The basic results of the 1939 work, based on the presence of electron conversion radiation of bromine, may be considered to be the qualitative confirmation of the theory clarifying the phenomenon of nuclear isomerism in metastable nuclei. The problem concerning the detailed quantitative comparison of the theory of metastable states in atomic nuclei with experiments was to be the object of studies in 1940.

Besides these items, the laboratory started work on the construction of an electron accelerator (quadratron) invented by Ye. L. Khurgin, a worker at the LFTI. The first model is designed to accelerate 100-kv electrons to 3 megavolts. Many parts of the accelerator have already been constructed and tested.

3. Fast Electrons Laboratory

Laboratory Head: Doctor of Physico-Mathematical Sciences, L. A. Artsimovich

Projects of the Laboratory for 1939 include studies of the angular distribution of fast electrons scattered by the nuclei of various elements. In connection with these studies a magnetic spectrograph with double focusing of electrons in a longitudinal field was constructed in 1939 and its operation tested; measurements will be performed in 1940.

At present, the whole nuclear physics group suffers from the lack of technical foundations, which makes further work impossible. Taking

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this matter into consideration, SNK (Council of the People's Commissariat) granted the Institute funds to construct a powerful cyclotron, the construction of which is supposed to start in 1940.

III. Molecular Physics Group

1. Polymers Laboratory

Laboratory of A. P. Alexandrov and P. P. Kobeko

Basic studies were devoted to problems of plastic deformation of rubberlike plastic materials over a wide range of temperatures (-180 to +200 C). By means of measurements of mechanical and electrical relaxation characteristics of various polymers, their physical nature was determined; thus, for example, it was established that the relation between frequency and temperature of highly electrical bodies is determined by the ratio of the time of relaxation of the substance and the time of action of force undisturbed by structural changes. This last fact is very important in the manufacture of plastic products intended for dynamic use. Interesting work was performed by N. Zhurkov, a scientific worker of the group, who succeeded, after studying the destructive effect of oxidizing processes, in finding a method for rolling sodium divinyl rubbers without decreasing at the same time their mechanical strength, as would happen in the case of the methods employed in U. S. factories.

2. Mechanical Properties Laboratory

Laboratory Head: Academician N. N. Davidenkov

The work of the Laboratory consisted of extensive studies of the cold brittleness of steel. The main problems that were supposed to be solved in 1939 were the following:

(1) Determination of the test criterion for judging the tendency of steel toward brittleness; study of rational methods of brittleness tests

(2) Determination of the effect of thermal and mechanical treatments on the brittleness of steel

(3) Processing of the greatest number of commercial steels with respect to their tendency toward brittleness and evaluation of their ratings

(4) Processing of methods for computing impact brittleness by the introduction of the new concept of "marginal viscosity", analogous to "safety factor" in ordinary calculations.

The solution of such problems is not mainly of theoretical interest but mostly of practical value. The Laboratory is cooperating with a number of plants by means of consultations and work contracts.

After having outlined the main works of the Institute in 1939, we consider it useful to note the basic and most serious problems which the Institute still faces in 1940:

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(1) Further perfection of photocell and rectifier types developed by the Institute and widespread introduction of these products into industry and engineering

(2) Creation of strong-current thermoelectric apparatus and sensitive receivers of radiative energy

(3) Development of theories of rectifiers, photoeffects and thermoeffects

(4) Obtaining polymerized materials with given properties - in particular, higher mechanical strength and thermal resistance

(5) Further improvement of the quality of resins and rubbers, and also improvement of the techniques of rational production of automobile tires

(6) New dielectric gases and gas-filled high-voltage cables

(7) Design and construction of a powerful electrostatic generator with high efficiency

(8) Establishment of the existence of the temporarily hypothetical particle called the neutrino

(9) Construction of a powerful cyclotron

(10) Construction of a quadraton

(11) Thorough and manifold study of the fission of heavy nuclei under bombardment by neutrons.

And, finally, we should note still another important problem - namely, the education of physical-science cadres that are able to establish physics as the foundation of our technical progress.

Submitted to the Editor, 14 February 1940.

2. Excerpt From Article Written at the OSPAM Company, Germany, 1944

GENERAL PROGRAM SUGGESTED FOR APPLICATIONS OF SEMICONDUCTORS BASED ON SCIENTIFIC CONSIDERATIONS

Introduction

Problems connected with semiconductors are closely related to recent work on the structure and properties of solids and have become an important factor with regard to problems connected with the electrical conductivity. It can even be expected that the solution of these problems will be aided to a large extent by the data obtained by investigating semiconductors. The reason for this is that electrons in metals are not present in their ordinary state, but are anomalous because of their high concentration. This is not the case in semiconductors; the concentration is lowered to such an extent that the electronic gas can be treated according to the laws of classical thermodynamics. The electronic particles are not free, however, like gas particles in an ideal gas, but move as charged particles in the periodic potential field of the ionic lattice of the solid. This causes difficulties, but, on the other hand, makes investigations especially valuable and fruitful. Further, it results in a number of technical applications, some of which are listed as follows:

A. How Does the Electronic Gas Behave in a Semiconductor?

(1) The determination of the free path of electrons in thin filaments and films (Method by Fucken).

(2) Determination of the number of free electrons.

a. From the absorption curve in infrared

b. From induction in a nonhomogeneous electrostatic field

c. From the Hall effect

d. From the weighing before and after reduction with hydrogen

e. From the change of gas pressure in a closed oxygen-fitted quartz tube after heating to elevated temperature

Technical Applications: Bolometer for light and high frequency.

(3) How does heat conductivity change with concentration of electrons? (Law of Wiedemann-Franz)

Technical Applications: Discovery of good heat conductors which are poor electrical conductors. Are there any better ones than aluminum oxide? Discovery of good electrical conductors with poor heat conductivity.

(4) What are the forms of the four magnetic-caloric effects for semiconductors? (Nernst, Ettinghausen, Hall, Righi-Leduc)

(5) Are there any throttling effects in semiconductors? (Gay-Lussac)

(6) Possible determination of the position of the energy bands of electrons by using ultrasound.

(7) Relations to lattice potential. Determination with very soft X-rays.

(8) Changes of concentration and mobility of electrons at high and low temperatures. Validity of the e-function for precision measurements.

(9) Relation between TC (temperature coefficient) and electronic concentration and lattice structure. Continuation of measurements of barium, strontium, and calcium perovskites, which have a positive TC up to 2 per cent per degree C. (Iron has 0.6 per cent per degree C.) This is a great mystery! There is no theoretical explanation for it.

<u>Technical Applications</u>: Construction of resistances with highly positive, negative, and zero TC. Possibilities unlimited, such as the generation of oscillations by the use of resistances having negative characteristics. Stabilizing of current and voltage.

(10) Investigation of transmutations between reduction and oxidation semiconductors. Continuation of the work of Professor Hilsch at Erlangen, with regard to PbS at low temperatures, and works on UO_2.

(11) Continuation of work on thermoelectric forces. It is known that semiconductors have very high thermoelectric forces.

<u>Technical Applications</u>:

a. Physical measuring devices such as pyrometers and hygrometers

b. Utilizing heat of the sun for power

(12) Are the sources of electrons visible in the electronic microscope?

(13) Relations between the specific form of electronic excitation in semiconductors for selective absorption and emission of light.

Technical Applications: Electrical selective radiators of light (similar to gas incandescent light) following considerations of Skaupy.

(14) Relation of color and electrical conductivity. Measuring of color of titanium dioxide spinels and comparing with the grey scale of Ostwald. Discovery of the green semiconductor ZnO-CoO.

B. Preparative Chemistry, Crystallographic and Chemical Investigations.

(1) Relation of typical properties of semiconductors with the number of phases. The modern idea is to prefer single phases. This idea has established the leadership of Osram in this field. Is it possible that the highly positive TC of perovskites is caused by their multiple phases?

Study of systems of mixed crystals. Diagrams of melting points of two component systems.

Base investigations on previous work done on artificial gems.

Technical Applications: High-load resistors such as those used for heating purposes. High-load resistors of small dimensions.

(2) Relation of the properties of semiconductive resistors to the degree of reduction.

<u>Technical Applications</u>: Improvements to be made of present-day resistors. Decrease of scrap in production.

C. <u>Phenomena on the Contact Surfaces Between Two Semiconductors of Different Types and Between a Semiconductor and a Metal</u>

(1) Catalysts and active oxides. Is there any relation between the two types of semiconductors and the phenomena noted in catalysts so far as oxidizing and reduction reactions are concerned? Is there any relation between catalytic action and concentration of electrons?

<u>Technical Applications</u>: Improvements to be made in catalysts.

(2) Continuation of work on the effect of Johnson-Rahbek.

<u>Technical Applications</u>: Very simple single-stage relays having an amplification factor of 10^8 to 10^{10}. Electrical clutches, mechanical oscillation, loudspeakers, motors, etc. Seeing eye for the blind, according to suggestions of Professor Knoll.

(3) What causes the noise of ceramic resistances? (Johnson's effect)

<u>Technical Applications</u>: Resistors with low noise level.

(4) Measurements of electrical potentials caused by passing electrolytic liquids along semiconductors.

Technical Applications: New source of electrical energy?

(5) Work on the validity of Schottky's theory about blocking-layer rectifiers.

Technical applications: New blocking-layer rectifiers without the disadvantages of the ones made today: CuO and Se rectifiers have only small blocking potential and fail at elevated temperatures.

(6) Is it possible to control electric current statically by using such a blocking-layer rectifier?

Technical applications: Development of systems consisting of one single solid body and acting like an electronic tube for the amplification and generation of oscillations. Example: Generation of a-c from d-c.

(7) Relation of surface resistance to mechanical pressure.

Technical Applications: Current regulators similar to the mechanical carbon regulator of the Pintsch Company. Advantages would be better constancy and higher load capacity.

(8) Transfer of energy from an electrically heated semiconductor to a cool gas.

a. Measurement of the accommodation coefficient of gases

b. Precision method of measuring the heat conductivity of gases according to Schleiermacher

c. What causes the three characteristic lines in voltage and current of resistance made of semi-conductors? Measurement of the distribution of temperature according to method by Toepler using striation apparatus

<u>Technical applications</u>: Production of resistors with any desired characteristic. Sensitive method for measuring gas currents. Continuous method of gas analysis. Apparatus for measuring oxygen content of gases according to the effect of Senftleben. Apparatus which directly indicates low gas pressures (already developed). Apparatus for measuring inclinations or rolling angles.

D. Investigation of Secondary Emissions of Semiconductors

Until now, this has been done only on metals and insulators. What is the relation of the primary electrons to the conducting electrons?

<u>Technical Applications</u>: Cathodes, amplifiers (multipliers), and oscilloscopes (working beyond the photoelectric limit of 2.7μ).

E. Relation Between Phosphorescent Materials and Semiconductors

Do conductive electrons influence the phenomena of luminescence? Some materials are known which are semiconductors as well as luminescent materials, such as ZnS, CdS, etc.

Technical applications: A light source which is luminescent by passing electric currents through it and without heating.

F. Mathematical Theory of the Position of Energy Bands

Quantum mechanical calculations of cubic crystals such as Mg-Ti-spinel, ZnO-CoO.

3. Uspekhi Fizicheskikh Nauk, 1947, Vol 33, No. 4

THIRTY YEARS OF SOVIET ELECTRONICS

S. Yu. Luk'yanov

Photoelectricity

In 1913, A. F. Lukirsky studied the photoeffect with crystals and, while working on X-rays, developed a new method of spherical condenser which was used by Lukirsky and Prilezhayev in work, beginning in 1926, on photoelectric effects at metallic surfaces. In this work, the measurement of the energy of the photoelectrons and the work function was made by the method of retarding potentials. The application of the spherical condenser transformed the method of retarding potentials into one of the most accurate and reliable methods of determining the work function. The motion of photoelectrons in the field of a spherical condenser can be fully calculated beforehand from the geometrical dimensions of the apparatus; the maximum energy of the photoelectrons can be determined with a high degree of accuracy, and the possible causes of errors can be determined or excluded.

In addition to the invention of this valuable method of investigating photoeffects, the great significance of the work of Lukirsky and Prilezhayev lies in the fact that it provided a strict quantitative verification of Einstein's photoelectric equation. The correctness of this equation was verified to a high degree of accuracy. At the same time the numerical value of Planck's constant was determined with great accuracy and immediately attempts were made to find experimentally, by the photoelectric method, the energy distribution of electrons in metals.

Some years later there appeared the theoretical work of I. Ye. Tamm, in which a theory of the external photoeffect for the case of a clean metallic surface is developed by the method of wave mechanics. Discussing the question of the relation of the electrons to the crystalline lattice and the conditions under which the absorption of quanta by an electron of the metal did not produce a violation of the law of conservation of impulses, Tamm arrived at important conclusions concerning the presence of dual forms of the external photoeffect of "surface" and of "volume" origin. The "surface" photoeffect is connected with the sudden change of potential energy at the boundary of the metal, and the "volume" effect with the potential "relief" inside the metal (periodical field of the ions in the lattice). Tamm's theory served not only to clarify the causes of the appearance of selective maxima on the curves for the spectral distribution of photocurrent in pure metals in a number of cases, but also, shortly afterwards, drew attention to other cases of electronic emission at metallic surfaces.

The mechanism of selective photoeffect in the case of a complex surface was discussed in the works of Lukirsky and Ryzhanov, while the interpretation of spectral selectivity for pure metals, arrived at from the optical constants of these metals, was given for a number of cases by Lukirsky and Khurgin. This latter work was connected with the general series of studies carried out by AYVS on optics and on photoeffects for alkaline metals, and is one of the most important works in this field.

In later years, in the field of photoelectricity, as well as in the field of thermionics, the attention of physicists was concentrated not on the study of properties of pure metals but on research on complex photo-cathodes of various types. From the invention of the cesium oxide photo-cathode in 1930 until 1937, this was the main subject of most of the work on photoeffects. In the U.S.S.R. the properties of this cathode, which was so important technologically, were studied intensely; its tech-nology was worked out and its anomalous properties and the mechanism of its action were investigated.

In this connection, the outstanding study was the one conducted by Stalin Prize winner Timofeeva and her colleagues; from their laboratory came the first Soviet photoelement of high sensitivity with a cesium oxide cathode. Timofeeva and Pyatnitsky first began the study of the energy distribution of the photoelectrons, which was essential for understanding the mechanism of the action of this photocathode. Later, Kushnir and his colleagues successfully continued the study of both this and other complex cathodes. Khlebnikov, together with Sinitsyn and Saytsev, studied the properties and technology of various modifications of the cesium oxide

cathode and investigated its spectral characteristics, fatigue, and the distribution of sensitivity on the surface. Finally, in 1944, the work of Morozov and Butslov appeared, which was rich in experimental material. In this work the relationship between the photoelectric and optical properties of the cathode and the thickness of the semiconducting layer was observed. The experimental data obtained in this work made possible a new appraisal of the complexities of the action of the cesium oxide photocathode and, in particular, refuted various constructions developed by de Bur.

In 1936, the antimony-cesium photocathode was discovered. A year later the first Soviet work on the subject appeared, in which Lukirsky and Lusheva described the properties of photoelements with cathodes of this type. At this time the technology for this cathode was still undeveloped, the mechanism of its action was unknown, and its properties had been studied very little. Even in this first work, surprising and ingenious explanations of a number of the newly discovered anomalous properties of the photoelement with the new cathodes were given. In particular, the presence of saturation with photoelements in vacuo is explained by the great longitudinal resistance of the cathode and the appearance on it, before illumination, of a fall of potential. Consequently, a "sliding" photocurrent appears, increasing at the expense of secondary emission; this current increases with the voltage and is superimposed on the initial current at the cathode. Later, when the value of the new cathode became clear to physicists and when its remarkable properties (great photosensitivity, stability in operation, and simplicity

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of manufacture) aroused widespread interest, a large number of works on antimony-cesium cathodes appeared; the overwhelming majority of these were from Soviet scientists. The first publication in the U. S. concerning the new photoelements appeared in 1941, and there is no doubt that not only have antimony-cesium photoelements been more fully studied in the U.S.S.R. than in England or the U. S., but also that its applications in technology were made earlier and are more widespread. It is possible to mention only some of the many questions concerning this work in this article.

In 1939, Prilezhayev studied the properties of antimony-cesium cathodes in equilibrium with cesium vapor through extensive experiments carried out by the method of the spherical condenser. This work of Prilezhayev, which is closely allied to the famous researches of Langmuir concerning the absorption of atoms on metallic surfaces, contributed much to the understanding of the process of activation of the cathode and the mechanism of its operation.

In the interesting and fastidious studies of Vekshinsky, carried out in the laboratory of the "Svetlana" factory in 1940, the microstructure of the antimony-cesium cathode was studied (earlier work had been carried out on the cesium oxide cathode). In the study of the photoeffect of the surface of various elements, Vekshinsky applied his own method for the automatic recording of photocurrents very successfully. Later he successfully applied the results obtained by his method in his studies on the process of crystallization of thin metallic films of antimony in metallographic studies on alloys of various elements. For the latter, Vekshinsky was awarded a Stalin Prize in 1946. Thus, wide applications in completely

different branches of technology developed from photoelectric studies on the methods of obtaining and analyzing thin metallic films.

In 1939, S. Yu. Luk'yanov determined the quantum sensitivity of antimony-cesium cathodes by a new method; the sensitivity reaches the enormous value of approximately 1/4 electron per quantum at points of spectral maximum of sensitivity of the cathode. This development makes it possible to regard the new cathodes as very sensitive indicators for radiant energy of a given wavelength.

Later, Khlebnikov and Melamid showed that the antimony-cesium photocathode is also very sensitive in the ultraviolet region of the spectrum. They designed photoelements with thin-walled windows and successfully solved the problem of creating sensitive apparatus for recording ultraviolet radiation.

For research into the spectral characteristics of antimony-cesium cathodes, S. Yu. Luk'yanov used the well-known Fowler-DuBridge method for determining the work function in the case of a cathode of a semiconducting nature.

A number of studies on antimony-cesium cathodes have been carried out in the Institute of Physics in Kiev and in the All-Union Electrical Institute in Moscow. In particular, Morgulis and Dyatlovitskaya have investigated the emissive properties of these cathodes in detail, observing the effect of temperature and of the electrical conductivity of the layer on the characteristics of antimony-cesium photoelements. The work of the Kiev physicists in this direction has continued in recent years. Particularly promising is the recent work of Morgulis and Borzyak, in

which the relationship between the optical constants of an antimony-cesium cathode and its photoelectric properties was studied. The results of these experiments are of interest not only in the field of photoeffects, but also in the physics of semiconductors, since data concerning the behavior of electrons which are excited by light in a semiconducting medium can be obtained from them.

An interesting physical study on the antimony-cesium cathode was published in 1947 by Brezhnev, who studied the effect of an electric field on the photoelectric emission of this cathode (Schottky photoelectric effect). In this work Brezhnev first investigated, for a type of antimony-cesium cathode, the autoelectron emission for a semiconducting surface. Many efforts to introduce the new cathode into various fields of technology have been made by Khlebnikov who, together with Zaytsev and Siniteyn, has studied the luminous and electrical characteristics of antimony-cesium photoelements.

In concluding this survey of physical studies on photoeffects, we should mention the presentation of a new point of view concerning the mechanism of emission from complex cathodes by Khlebnikov in 1945. Relating the photoeffect from such surfaces with a power model of a semiconductor, Khlebnikov strongly criticized many points of de Bur's theory, in which the role of atoms of alkali metals absorbed on the surface of complex cathodes is undoubtedly overestimated. With its very logical approach, Khlebnikov's presentation can make a positive contribution to the search for new photo-cathodes and to the investigation of existing cathodes. Among the works on special technical applications of photoeffect, we should mention

Braude's work in 1937, in which a new and very ingenious apparatus designed for the television transmission of motion pictures was described. The essential part of this apparatus consists of a photosensitive metallic wire, on which is projected a line of frame to be transmitted. By setting up an electric field along the wire that moves with the speed of exposure, and collecting the photoelectrons emitted by the filament, we obtain in the collector circuit a photocurrent, the speed of growth of which will be proportional to the light signal from the element of the transmitted picture. Braude's system is a completely original solution of the problem and, as demonstrated by the Leningrad Television Center, is very suitable for the transmission of cinefilms.

Secondary-Electron Emission

In 1920, P. I. Lukirsky and N. N. Semenov conducted the first studies in the U.S.S.R. on secondary-electron emission; they measured the coefficient of secondary emission for mercury and studied its dependence on the energy of primary electrons. Because of the limitations of vacuum technique at that time, their numerical data are not considered accurate by present standards; nevertheless, their qualitative explanation of the observed dependence is completely valid.

L. A. Kubetsky's invention of the multistage electron-multiplier phototube in 1934 (this invention was duplicated shortly afterwards by Zworykin in America and by Weiss and others in Germany) aroused increased interest in secondary emission, and in later years a valuable stream of work has appeared on the physics and technology of secondary-electron emission.

In these works the mechanism of the phenomena for the simplest case of pure metallic surfaces was studied, principles necessary for understanding the processes occurring in complex cathodes were established, new surfaces having large coefficients of secondary emission were described, and numerous more efficient designs of electron-multiplier phototubes were suggested.

In 1938-1939, Vyatskin began the formation of a strict quantum-mechanical theory of the phenomena for the case of a pure metal. After criticizing strongly the theory suggested by Frolich, Vyatskin treated the whole problem of a pure surface in the light of the Sommerfeld model of a metal. The theory in this form was of established value and interest for analyzing experimental data on pure alkali metals in a field of low-energy primary electrons; however, this theory cannot accurately describe the phenomena of high-energy electrons for the case of ionization in connection with atomic ions. Later, in 1944, Vyatskin substantially developed and extended his theory. In his new work, secondary-electron emission is regarded as a phenomenon dependent on the complexity of the surface and on two-volume effects caused by the "free" electrons in the lattice and the atomic electrons. The volume effect for "free" electrons determines the precise structure of the energy-distribution function for secondary electrons, while the surface effect gives the basic form of the energy-distribution function. Both volume effects combined provide approximately 10 to 20 per cent of the secondary emission. Also of interest for the theory of electron emission from metals is Vyatskin's theory, developed in the same work in 1944, concerning the absorption of electrons (primary and secondary) inside the metal because of interaction with the electrons of the metal.

In the theoretical works of Kadyshevich, secondary emission is regarded as a volume effect, like a process of ionization, proceeding in the mass of the secondary cathode. The ionization theory agrees with experimental values for electrons, and later applications to semiconducting surfaces explained the causes for the great increase in this coefficient for complex cathodes. Actually, the value for this increase agrees only very approximately with the theory, but it must be remembered that previously no satisfactory explanation existed concerning the behavior of slow electrons produced during emission in the mass of the cathode, particularly when the internal structure was complex, as in the case of present-day emitters.

Extensive experimental research on secondary emission has been carried out. In 1936 the work of Afanaseva and Timofeeva, which preceded the well-known work of de Bur, made clear the important question of the increase in the coefficient of secondary emission for pure alkali metals, and it was shown that, for the latter, an increase in [illegible] was less than for other pure metals. Afanaseva and Timofeeva applied a new experimental method for the study of secondary emission - the deposition of layers of atoms of another metal in gradually increasing thicknesses on metallic backing - which proved very useful for studying the mechanism of the phenomena and was widely used afterwards.

The work of Khletnikov and his colleagues clarified the part played by absorbed gases. Later, the accurate experiments of Morozov (1941) not only gave a reliable and accurate value for the coefficient of secondary emission for many pure metals, but also confirmed the

results of Kushnir and his colleagues concerning the dependence of secondary emission of pure metals on temperature, within wide limits. In the same work, the effect of the transition of the metal through the melting point on secondary emission was studied.

In 1937, S. Yu. Luk'yanov and Bernatovich made a very accurate study of the dependence of the coefficient of secondary emission on the angle of incidence of the primary electrons. The increase of secondary emission for obliquely incident primary electrons was established both for pure metallic surfaces and for complex cesium oxide emitters. This problem was later studied in detail by Kushnir and his colleagues. In a number of works (1941-1946), they studied the effect of the angle of incidence of the electron beam on the total secondary emission, and also conducted difficult experimental research on the effect of the angle of incidence upon the energy-distribution function for secondary electrons. The dependence of the distribution function for secondary electrons on the angle of departure was also studied. In Kushnir's laboratory the study of the dependence of secondary emission upon the angle of incidence of the primary beam is important for the design of electron-multiplier phototubes, and the explanation of the experimental data obtained is important for understanding the mechanism of the phenomena. In particular, some ideas developed by Luk'yanov and Bernatovich in their work (see above) were used for the development of the ionization theory of secondary emission.

Secondary emission from pure semiconductors was first studied in the works of Afanaseva, Timofeeva, and Primer, and for dielectrics by

Vudynsky as well as by Kosman and his colleagues. In this latter particularly outstanding work, new methods were utilized.

The study of efficient emitters, i.e., surfaces with large coefficients of secondary emission, is closely connected with the so-called Malter effect. This term is applied to the superposition, in a number of cases, of autoelectronic emission on the real secondary emission from a surface. It is often very difficult to separate the results of these two effects: real secondary emission and the Malter effect. This problem is of great importance both theoretically, from the standpoint of explaining the mechanism of secondary emission from nonmetallic surfaces, and practically, because efficient emitters of secondary electrons are found among these types of surfaces. Some investigations, headed by Timofeeva and her colleagues, believe that, in general, the substantial coefficients of secondary emission of semiconducting emitters (> 2/3) already indicate the presence of the Malter effect in a special form, while at the same time others (Morgulis, Zernov, Khlebnikov) believe that real secondary emission can give values of σ amounting to 1 to 12.

Consequently, at present, there is a whole series of works by Soviet physicists dealing with studies of emitters of the semiconducting type. In the course of this work, the energy distribution of emitted electrons for a number of surfaces has been explained and two groups of electrons, real secondary electrons and "autoelectrons", have been discovered, in the case of typical Malter emitters. In addition, measurements have been made of the fall of potential in a layer of a semiconductor giving the greatest value for σ, and the existence of intermittent

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transitions from emission of the usual type to Malter emission with changes of thickness of the semiconductor (Zernov) has been demonstrated experimentally. The temperature dependence upon the density of the primary current, the speed of primary electrons, etc., has been determined for many efficient emitters.

All of these studies, in addition to providing data of purely physical interest also have placed at our disposal a valuable "arsenal" of secondary-emitting surfaces, possessing high coefficients of secondary emission, reliable in operation, and capable of considerable loading. Of particular interest in this connection is the magnesium oxide emitter, developed by Aranovich in Timofeeva's laboratory, having a value for σ of the order of 30 to 50 (instead of the usual value in technology of 8 to 10) and withstanding temperatures up to 1000 degrees C. Mention should also be made of the copper-sulfur-cesium emitter, developed in Kubetsky's laboratory, which has proved very suitable for application in a photomultiplying magnetron with the cathode on the glass envelope.

The pioneer in the technological application of secondary emission has been L. A. Kubetsky. He not only described an actual design for a multistage amplifier, but in 1934 he built a working model of the apparatus. In recent years Kubetsky, Vekshinsky, and Timofeeva have created numerous, very sensitive variants of photomultipliers and electron tubes using secondary emission in the laboratories of the "Svetlana" factory, in the All-Union Electrical Institute, and in the Institute of Telemechanics. The main obstacle to the development of these tubes in recent years has been the lack of sufficiently efficient and heat-resisting cathodes; this difficulty can be considered surmounted.

Original expectations of a revolution in amplification technology, to be brought about by the introduction of electron-multiplier phototubes, have proved to be over-optimistic. At the present time, in the competition between the two systems - vacuum-tube amplifiers and electron-multiplier phototubes - victory seems to lie with the older system, but it must be remembered that vacuum-tube circuits have already been very fully developed. Multipliers suffer from a number of shortcomings; they are not standardized to the same extent as vacuum tubes and are less stable. Their main advantage lies in great amplification of weak h-f signals, for example, in television, because the signal-to-noise ratio is higher than it is in vacuum-tube circuits. Application to talking films is possible, but the question as to which is the most efficient system (vacuum-tube amplifier, photomultiplier, or a thallium-sulfur photoelement with a blocking layer) still remains unanswered.

Thermoelectronic Emission

During 1911-1913 Langmuir and Childs solved the problem of calculating the increase in electron current in vacuum in the presence of a space charge, assuming absence of initial velocity, for the plane and cylindrical cases (Langmuir's 3/2 Law). For the cylindrical case the solution was, however, only approximate, and in 1923 an exact solution was obtained simultaneously and independently by Boguslavsky in the U.S.S.R. and by Langmuir and Blodgett in the U. S. Boguslavsky's work contained a full and strict treatment of the problem, but, as it was published after

the author's death in 1924, in a journal with limited circulation, it has unfortunately remained unknown to the majority of later investigators.

Another noteworthy early work in this field was that of Pavlov and others, published in 1923, dealing with research on the movement of electrons between two plane grids. In this work the presence of initial speeds (assumed to be constant) for the electrons was studied and a certain inexactness was pointed out in the solution, i.e., for the given conditions, the value of the current in the apparatus was not fully determined by the value of the potential on the electrodes. This work was also forgotten and Pavlov's work was duplicated, considerably later, in the works of foreign investigators.

The first Soviet work on radio tubes was carried out in the years 1918-1919 when Bonch-Bruevich and Ostroumov in the Nizhegorod Radio Laboratory laid the foundations of the Soviet electrovacuum industry and carried out the first experimental research on electronic phenomena in tubes.

Experimental research by Soviet physicists on thermoelectronic emission from various surfaces appeared in later years. The main portion of this work was carried out under the direction of Vekshinsky and Lukirsky in the physics laboratory of the "Svetlana" factory. This factory played a unique role in creating Soviet electrovacuum apparatus. Among these works, the fine experiments of Vekshinsky, Lukirsky, Sezina, and Tsareva (1930) concerning the effect of layers of "foreign" atoms absorbed on the surface of the metal on thermoelectronic emission should be mentioned. These experiments, and also the studies of Ptitsyn, Berdennikova,

Morgulis, and his colleagues, Ravdel, Anselman, and Dozlyakovsky, were the starting point for extensive work on the study of complex incandescent cathodes of various types, and for the development and refinement of the technology of the thoriated and carbon cathodes, and later the oxide and barium cathodes.

Much valuable work was done in the field of electrovacuum technology by Ivanov, a recently deceased engineer and physicist of the "Svetlana" factory. A leading part in creating Soviet radio tubes has been played by Vekshinsky, Shaposhnikov, and Zusmanovsky. The latter, together with Katsman and Moshkovich, was awarded a 1941 Stalin Prize for the invention of a low-voltage amplifier.

Among the studies of a purely physical character, mention should be made of the works of Rutkevich, Morgulis, and Dyatlovitsky who studied electron emission from a thoriated tungsten filament. Dobretsov and Morozov investigated the evaporation of barium on tungsten and determined the heat of absorption of the atoms of barium, and also the time of absorption of barium with various coatings and temperatures.

The Schottky effect for thermoelectronic emission was studied in the works of Dobretsov and Morgulis. In one of the later works (1 41), Dobretsov undertook the exact determination of the change in the work function under the influence of an external electric field, using a thermal method. He made careful measurements of the latent heat of evaporation of electrons with various external fields and showed that these measurements of the latent heat of evaporation agreed with the measurements for the work function, as given by Schottky's theory.

Interesting studies on the investigation of the behavior of oxide cathodes under impulse conditions were recently (1944-1946) published by Andrianov, Morgulis, Kalashnikov, and others. The detailed explanation of this problem has great significance for the solution of many problems of present-day radio technology.

The complete description of Soviet work on radio tubes belongs to the field of radio technology and cannot be given here, but one series of studies in which Soviet scientists have contributed much that is new and original should be mentioned.

The development of microwave technology in connection with the successful development of a magnetron oscillator has aroused increasing interest in the explanation of magnetron operation. In a number of articles, the publication of which began in 1934-1935, Grinberg, together with Lukoshkov and other workers of the "Svetlana" factory, calculated the fields in a slotted magnetron and, using Grinberg's graphoanalytical method, were able to plot the electron trajectories in these fields. Consequently, it was possible to explain fully the causes of the negative resistance of the magnetron and disprove the earlier inaccurate theory of this phenomena. Also of considerable importance to radio technology is the explanation of problems concerning the nonslotted magnetron, the calculation of the fields, the determination of the dependence of the current strength on the magnetic field, etc. For the "spherical" magnetron, the full solution was first given in 1938 in a study by Grinberg and Volkenshtein which states, in particular, the formulas for determining the wavelengths of the transient oscillations and their dependence upon the dimensions and upon the applied fields.

Another interesting study in microwave technology concerns the theory of the passage of an electron current near the limits of its space charge through a plane diode of such high-frequency applied voltage that the period of the high-frequency field is comparable to the time of flight of the electrons through the apparatus. In 1935, Grinberg first gave the full solution for a cylindrical diode in addition to new investigations of the plane case. In the work of Grinberg and Blizhyuk in 1938, the corresponding calculations were given for determining the values of the complex impedance of a cylindrical diode at high frequency. In addition, Grinberg investigated in detail the initial stages of the passage of an electron current through a diode when an impulse voltage was switched on to the anode (motion of the "electron front" and the accompanying formation of a space charge).

Mention has been made above of the importance of theoretical work in investigating the magnetron. Experimental development and research on magnetrons, apart from that in "Svetlana" factory, was first carried on in Moscow and later in the Gorky Physicotechnical Institute, which has also carried out valuable work on electron-beam tubes. In addition, wide experimental research on the magnetron has been done by Slutskin, who has also made various theoretical calculations on the same subject.

Surface Ionization and Ionic Emission

The phenomenon of surface ionization was observed by Langmuir and Kingdon during 1923-1924, for the case of the ionization of cesium atoms on the surface of incandescent tungsten. Then the well-known

Langmuir-Suk formula was devised for the temperature dependence of this phenomenon. The subject matter of this research (cesium on tungsten), however, did not permit a thorough check of this formula to be made, since the atoms of cesium reached practically 100 per cent ionization over the whole temperature range convenient for the investigation. Therefore, it was not until considerably later (in 1934) in the works of Dobretsov and Morgulis on the ionization of potassium, sodium, and barium on the surface of tungsten, molybdenum, and tantalum, that the temperature dependence for ionic emission was first satisfactorily investigated and the applicability of the Langmuir-Suk formula was fully verified.

Particularly fine experiments were carried out by Dobretsov, who used the very thorough method of molecular beams. It should be emphasized that the interesting case of sodium on tungsten (the ionization potential for Na is greater than the work function for W) had not previously been generally investigated. In 1934, Morgulis also studied the reverse phenomenon - the neutralization of ions of alkali metals on metallic surfaces.

Surface ionization on complex cathodes was first studied in the U.S.S.R. In 1934, Dobretsov undertook the investigation of surface ionization for thoriated tungsten and, subsequently, he accurately analyzed all aspects of this phenomenon. The interest in and the significance of this work extend far beyond the study of the effect of surface ionization. The first experimental demonstration of the presence of "mottled structure" in complex cathodes occurred in the course of this work. Electron-optical research was carried out later and the well-known discussion of Langmuir,

Kingdon, and Bekker concerning Mottling of Thorium on Tungsten in 1934 was of a purely hypothetical nature. In this way, surface ionization can be used as a new method for studying the structure of complex cathodes. It also successfully supplements thermoelectronic research on the portions of the cathode with the minimum work function, while surface ionization proceeds particularly readily on the portions with the maximum work function.

Later, in 1936, Dobretsov, as a result of discussions with Morgulis, showed that the effect of an electric field on surface ionization, over a wide range of field strengths, produced a Schottky effect for ions. In 1937 and 1938, Dobretsov, Konozenko, Morgulis, and Dyatlovitska first studied the effect of an electric field on surface ionization of thoriated tungsten ("the anomalous Schottky effect for ions"). Studies in this branch of the subject were first suggested by Soviet physicists, who later achieved complete explanations of the phenomena.

In 1937, Ionov, acting on a suggestion by Lukirsky, began the study of surface ionization of atoms forming negative ions. In 1940, Dukelsky and Ionov published a work detailing their investigation of the formation of negative halide ions during the reaction of alkali halide molecules with the surface of incandescent tungsten. These studies, continued later by Ionov, undertook the verification of the applicability of the Langmuir-Saha formula to ionization of this type. The value of study along these lines includes the possibility of the direct measurement of electron affinities of various atoms, which is very difficult to determine by other methods. Similar studies have been carried on for a number of years in Tashkent, where the experiments, begun in 1935 by Starodubtsev

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in Lukirsky's laboratory, on the surface ionization of alkali halide salts were continued. It was clearly shown that the study of the temperature characteristics and the absolute coefficients of this type of ionization provides a means of determining the heat of the reaction on the surface of the metal. Shupp and Arifov continued the study of positive ionization of salts and the negative ionization of halides on thoriated tungsten on the same plane.

Work clearly related to these questions has been conducted by Pavlov and Morozov (1935 to 1940) on the study of the ionic emission of various chemical compounds, and by Pavlov and Starodubtsev on the investigation of the reactions of slow and fast ions with metals and with films of semiconductors. The large amount of experimental material obtained from these experiments needs further development and systematization, since it could be developed into a new original section of surface chemistry.

Quite recently (1946 and 1947), Dobretsov, Starodubtsev, and Timokhina observed a new type of surface ionization, the ionization of atoms of metals on thin films of oxides of the same metals. The observed phenomena do not fit into the framework of the usual theory and deserve further intensive study.

Electron Diffraction

In comparison with other fields of electronics, the Soviet works on electron diffraction are few in number, but many of them have proved vital for development in this field.

First, the work of Tartakovsky should be mentioned. He was a pioneer in studies on electron diffraction and has carried on this work since 1927 in Leningrad and Tomsk. Interesting studies were conducted by Kolpinsky in the Physics Institute of Leningrad State University on the study of polycrystalline thin films with orientated crystals, and by Kolpinsky and Fok who investigated, both theoretically and experimentally, electron diffraction from deformed crystals. In the same place, Alikhanyan and Kosman studied electron diffraction with "relativistic" electrons.

Lushkarev and his colleagues investigated the diffraction of slow electrons and demonstrated the dependence of the refractive index of the electron waves on the speed of the electrons. Lashkarev and Usyskin used electron diffraction to determine the space structure of the ammonium chloride molecule.

In addition to experimental work in this field, theoretical studies have been made by Tartakovsky, Lashkarev, Kalashnikov, and others.

Electron Optics

The problems of electron optics did not attract the attention of Soviet physicists until a much later date, since all the published work on this subject has appeared in the last seven to eight years. Nevertheless, the work of Soviet scientists has substantially enriched this branch of electronics by theoretical research, new ideas, and original designs for electron-optics apparatus.

The importance that is attached to the artificial production of ions with great energies is well known in present-day nuclear physics.

The best method for obtaining such ions is the cyclotron; however, the relativistic increase in the mass of the particles during their acceleration effectively limits the possibilities of this remarkable instrument. For many years it seemed that the only way of reaching higher energies would be to increase the voltage; this would require a larger clearance between the poles and would increase the size of the powerful cyclotrons which were already quite massive. A completely new principle was introduced by Veksler in 1945, when he suggested the use of "autophasing", a method he had discovered. It appeared that, by introducing slow variations of frequency, it was possible to effect a sudden increase in the limiting energy of the ions without changing the size of the cyclotron. His work was soon repeated in the U. S. and, at the present time, the cyclotron with modulated frequency is one of the most perfected tools of applied nuclear physics.

Interesting work has also been conducted by Soviet physicists toward the solution of the problem of accelerating electrons. In 1939, long before Kerst's well-known work, Kelman, Korsunsky, and Lang, in the Kharkov Physicotechnical Institute, designed a magnetic electron mirror and had begun work on its application to the construction of a "quadratron", an apparatus for the repeated acceleration of electrons. Unfortunately, this work and the theoretical researches of Terletsky (1941), who, independently of Kerst, re-examined the ideas of Videroe on the creation of an electronic transformer, were interrupted by World War II.

It was in Kharkov also that Korsunsky, Kelman, and Petrov first suggested and realized experimentally the construction of a light-intensity

β-spectrograph with a nonhomogeneous magnetic field, which was used to obtain aberration-free focusing of wide-angle (40-degree) electron beams.

Of particular interest are the studies of Grinberg, published in 1942, on the general theory of focusing electrons in electrostatic and magnetic fields. The importance of this work lies in the fact that it gives some general laws for motion of charged particles under the influence of electrical and magnetic forces and these laws determine the conditions for the focusing of electron and ion beams. Long ago, certain special cases of the movement of electrons in electrical and magnetic fields leading to focusing of the electron rays were observed, which were analogous to the focusing of light rays by optical instruments. The analysis of these special cases was the task of theoretical electron optics, and many varied and interesting practical applications resulted from this work. For the further development of this science, however, the substantial development of theoretical electron optics was an imperative necessity. The necessity for the expansion of the theoretical bases of electron optics had long been appreciated by workers in this field, but, until the appearance of Grinberg's work, few advances had been made toward the solution of the general problems of electron focusing. The results obtained by Grinberg are the present foundations of electron optics, and, today, theoretical work in this field is almost complete.

Grinberg's solution of the problem was obtained by completely new methods which are of great interest from the standpoint of theoretical mechanics. In mechanics, the problem of the motion of a particle usually consists of defining a field of force and then investigating the motion in

this field. By this method, the geometrical forms of the trajectories are known only when the calculations are completed. In Grinberg's work, however, the basic problem of dynamics was, so to speak, "turned inside out". Because of the practical necessity of controlling the form of the electron trajectories, Grinberg set out to examine the possibility of determining the electrical or magnetic field required by a beam having a trajectory of a given form. This new approach to the problem was fully justified by its success, not only in explaining under what conditions the focusing of electron trajectories was possible, but also in providing formulas for determining the fields needed for beams of a given form.

In 1944, Artsimovich published an important theoretical work dealing with the observed electron-optical properties of emission systems. Such systems include all apparatus in which images of objects which emit slow electrons are obtained; examples are the emission-electron microscope, the television dissector, and the electron guns of Kinescopes. In spite of their great practical importance, the theory of such systems up to that time had only been developed in a very inadequate form. Artsimovich not only found an original method of solving the associated differential equations for the trajectories of the electron beams in these cases, but also produced a calculation for the resolving powers and main electron-optical aberrations of these systems.

In recent years, electron optics has been applied by Rik and Kormakova to the analysis of the trajectories of electron beams in electron-multiplier phototubes. Electron-optical researches have been carried out

for the incandescent cathodes by Morgulis and for antimony-cesium photo-cathodes by Brezhnev.

The most important item of the widespread work, carried out for several years in the State Optical Institute by A. A. Lebedev and his colleagues, was their creation of the first Soviet-built specimens of electron microscopes. In 1947, Lebedev, Vertsner, and Zandin were awarded a Stalin Prize for this work.

4. Bulletin of the Academy of Sciences, U.S.S.R., Section of Physics, 1946, Vol 10, No. 1, p 3

SEMICONDUCTORS AND THEIR APPLICATION

A. F. Joffe

Metal and liquid electrolytes have been widely used in electro-techniques and metallurgy for a long time. Their properties have been thoroughly investigated and are explained by modern theories. Contradictions which seemed inexplicable before have been eliminated, and a full quantitative correlation between the experimental data and those of the theory was obtained.

Solid dielectrics showed a series of inexplicable and contradictory phenomena which, for a long time, had been assumed to be anomalies.

As a result of lengthy investigations performed by members of the Physico-Technical Institute of the U.S.S.R., it was possible to define rules of the transition of ion current through solid crystals instead of considering these phenomena as anomalies, and to explain the mechanism of the basic phenomena.

Just as at the beginning of this century when the property of insulating material seems to have been very puzzling, so 15 years ago attention was drawn to semiconductors, which showed a series of particular properties, namely, the detection of high-frequency current, the rectification of alternating currents, and the presence of electromotive forces during illumination. Particularly these properties stimulated the application of semiconductors in industry.

Simultaneously, the discrepancy in the general conception of semiconductors appeared. V. F. Gouse showed that rectification could be obtained artificially by coating cuprous oxides with a layer of silicon dioxide, in which case the best rectification was attained when the layer thickness was about 10^{-5} centimeter.

It may be assumed as fact that the action of rectifier and photo-elements is related to the presence of the thin nonconducting layer, called by us "closing (blocking) layer".

It might be expected that the electrons extracted by the light during their transition through the "closing layer" into the metallic electrode would charge the latter negatively, but the type of photoelements known then, elements of cuprous oxides and titanium, produced a positive electric charge on the electrode.

It could also be assumed then that, in the rectifier, the passing currents transfer electrons from the semiconductor to the intermetallic electrode, but, in reality, this direction of the current was observed as "stopping" (blocking) in the rectifier made of both indicated materials.

During the contact of two bodies, it might be expected that the electrons would be transferred in the direction corresponding to the decrease of their energy, that is, from the body with the lower dielectric constant into the body with higher dielectric constant, but the investigation of a large number of dielectrics induced Cohen to state an empirical law that was directly contradictory to both the indicated assumptions. This empirical law read as follows: "Of the two contacting bodies, the one which possesses a higher dielectric constant is charged positively differently. This gives up its own electron".

Evidently, it is impossible to reach the conception of electrical properties of a substance before these controversies are cleared up. Wilson and Fowler proposed a theory of semiconductors on the basis of the wave mechanics, but this theory did not explain either rectification or photoelectromotive forces, which are the specific property of electronic semiconductors.

A series of theories has been proposed, attempting to explain the formation and the property of the "stopping (blocking) layer" in semiconductors. Despite the fact that each of these theories has some confirmation in the experimental data, it can be assumed that no one of the existing theories will present a full picture of these phenomena.

At the present time, several such puzzling phenomena can be explained, and, as always, a better understanding permits a better application of them to practical use. In the following, there will be given the results of our study of semiconductors.

The Most Important Results of the Investigation

Determination of the Numbers of Electrons, Their Conductivity, and Their Mobility

The basis of our theoretical concept is the well-known zonal picture of the energy equation of electrons derived from the quantum equation of the valence electron during the formation of crystals from individual atoms or ions. This picture is presented in Figures 1 and 2.

The direct methods of study of levels are the X-ray spectra of emission and absorption and the optical phenomena of the absorption of the internal photoeffect. However, up to the present time, neither X-ray nor optical spectra have been used for the determination of the system of the electron levels in semiconductors. This is one of the problems which we shall attempt to solve.

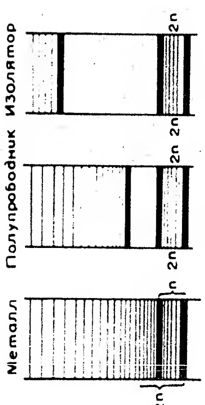
For the present, we are evaluating the property of electron levels according to indirect criteria, namely, electroconductivity, temperature changes, the influence of the magnetic field, and thermoelectric phenomena.

The sign and value of the Hall effect determines the positive hole or electron mechanisms of conductivity, and the constant R of this effect determines the number n of current carriers, $n = \frac{1}{eR}$, where e is the charge of the electron. The temperature changes of the Hall constant give the value of the energy-level separation for electrons: $E = \frac{d(\log R)}{d(1/T)}$. Finally, combining the measurements of the Hall effect with the value of electroconductivity, σ, we might determine the mobility, u, of electrons in a semiconductor: $u = \frac{1}{e} R\sigma$. The determination of the sign and the

value of the thermoelectromotive force could be used for checking the results obtained. The problem is more complicated where a complex mechanism of conductivity could be suspected. In such a case, the solution of this problem could be reached, as was shown by N. Davidenko, by the study of a given substance with different amounts of additions. With this method, it is possible to form a purely hole or electron type of conductivity and sometimes a combination of these two. For the determination of a definite number of carriers of these two types, their mobility, and effective mass, it is possible always to set up more equations than the number of existing values which have to be determined. Excess equations could be used for checking the accuracy of results obtained, and generally, this works quite well.

A typical semiconductor of high specific resistance is cuprous oxide, with a varying excess of oxygen (or, better to say, with a deficiency of copper) in comparison with the chemical formula Cu_2O. B. Kurtchatov and V. Geuse showed that cuprous oxide close to the stoichiometric formula at room temperature possesses a specific conductivity of the order of 10^{-10} $(\text{ohm-cm})^{-1}$. With the increase of absolute temperature, t , the conductivity of the cuprous oxide increases according to the law: $\sigma = \sigma_0 e^{-\frac{u}{2kt}}$, where u is equal to 1.44 electron volts.

To this, for cuprous oxide with an excess of oxygen, should be added an increment: $\sigma/u = Ae^{-\frac{U_u}{2kt}}$, for which U_u has a value close to 0.6 electron volt. With the increase of the oxygen excess, coefficient A increases, but the value of U_u slowly decreases. The following diagram (Figure 3) indicates the behavior of specimens of a different stoichiometric composition. On the abscissa, as customarily drawn, are plotted the inverse



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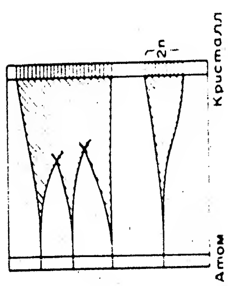
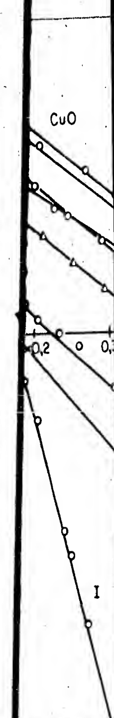


РИС 1

Рис - Fig
Атом - Atom
Кристалл - Crystal
Металл - Metal
Полупроводник - Semiconductor
Изолятор - Insulator



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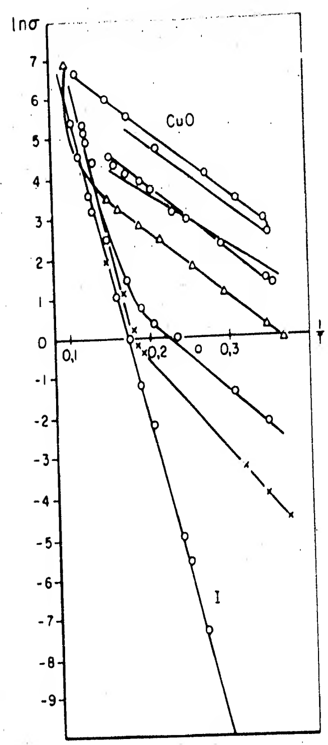

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values of absolute temperature and on the ordinate axis the logarithm of electroconductivity ($\log \sigma$). In such coordinates, as is well known, the slope (a straight line) defines the value of the energy, u, used.

The increase of conductivity with temperature in the poorly conducting semiconductors might be explained primarily as a rapid increase of the number of electrons in comparison with a slight decrease of their mobility. Therefore, the values of u calculated from the temperature curve of conductivity could be assumed as an energy barrier, E, to the release of free electrons.

The case of semiconductors with low resistance is completely different. Here, the temperature curve of conduc[illegible]ty depends to a greater extent on the decrease of mobility than on the increase in the number of electrons.

The high values of specific conductivity might be stipulated by (1) a slight overlapping of zones (as was proven by B. Davydov for bismuth), (2) a considerable number of impurity levels inside the free zone, or (3) a low value of forbidden zone of the order of 0.1 to 0.3 electron volt.

Among the materials possessing low resistance, Yu. Maslakovez and E. Devintkova investigated the electric, thermal, and thermoelectric properties of lead sulfide containing an excess of lead or an excess of sulfur. In the first case, the substance possessed electron conductivity; in the second case, hole conductivity.

Maslakovez and Dunaev established that the number of electrons does not change up to a certain temperature, which depends on the amount

of the excess of lead or sulfur. Above this temperature, the number of electrons increases as in the common semiconductors. The mobility of electrons decreases with increasing temperature according to a law very similar to that applied to metals (Figure 4a).

The changes in concentration of impurities or the value of the deviation from the exact stoichiometric formula does not change the mobility of charges but changes their number, which increases with the increase in concentration of impurities (Figure 4b).

Of the excess of lead or sulfur introduced into substances, only a small part is dispersed in the atom form and increases the number of the current carriers. The remaining part of the impurity coagulates and could influence the electrical conductivity only in the form of metallic bridges. With an increase of the temperature, the solubility of the impurity increases, and, with rapid cooling, the excess of the impurity remains for a long time in atom form and coagulates only very slowly and very gradually.

Up to 2 K, the electroconductivity of lead sulfide, with an excess of lead or with an excess of sulfur, retains its final value of the order 10^{-5} (ohm-cm)$^{-1}$ without being transformed into a superconductive substance (despite the data which could be found in the technical literature). Figure 5 shows the curve of resistance of lead sulfide in comparison with the resistance of lead.

Therefore, it might be assumed that the addition of lead or sulfur to the lead sulfide is completely dissociated, but the basic lattice of lead sulfide is an electron semiconductor with a forbidden zone of the order of 0.5 electron volt.

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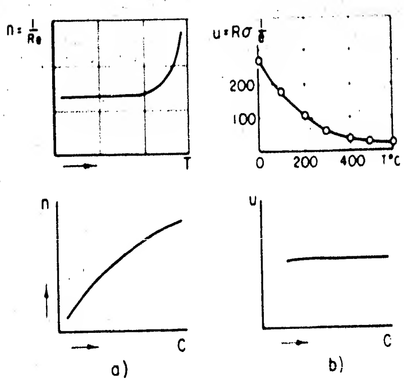

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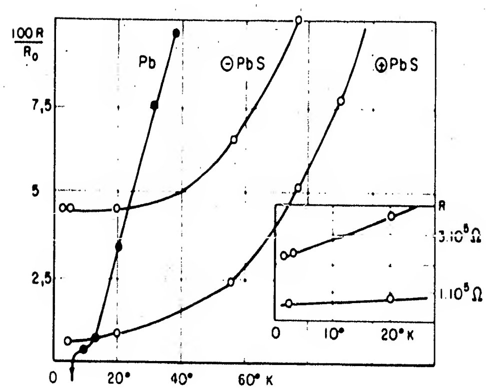

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For the determination of the energy barrier of good conducting semiconductors, it is impossible to use the temperature curve of conductivity, σ, which is determined by the curve of mobility at a constant concentration of electrons in a wide temperature range, but, even at such higher temperatures when a considerable increase of concentration might be observed, the influence of mobility could be compared with the rule of electron concentration.

Figure 6 shows the directly measured curve of electroconductivity plotted against absolute temperature for specimens of lead sulfide with different excesses of lead.

Figure 7 illustrates a temperature curve of concentration of electrons, n, of lead sulfides of stoichiometric composition and specimens with excesses of lead or sulfur. This relation is expressed in a common diagram: $\log n = f(1/T)$. This curve might be compared with the curve for the cuprous oxide indicated in Figure 3.

Analogous properties are also possessed by the compounds of antimony with metals of the first and second groups of the periodic system.

During the study of thermal conductivity of lead sulfide, depending on the concentration, n, of electrons of conductivity, Kaslukovez and Dunaov could determine the thermal conductivity of the lattice K_1, depending on the thermal conductivity of electrons. The conductivity of electrons indicated in Figure 8 by the shaded area is interconnected by the law of Wiedemann and Franz with electroconductivity. This area in a specimen with good conductivity reaches 10 to 20 per cent of the total value of K.

In the cases where the width of the forbidden zone does not exceed 0.1 to 0.2 electron volt, or if the distance $\Delta\mathcal{E}$ from the energy levels of additions up to the free zone is small, then even at room temperature all the levels of the free zone are filled up. The free zone is that which corresponds to kinetic energy up to 0.15 electron volt.

The increase of the number of free electrons could take place then only on a level of higher energy and will require an input of energy $\Delta\mathcal{E}$ equal to 0.15 electron volt.

Therefore, the energy barrier for electrons, calculated not only on the basis of the curve of electroconductivity, but also for the Hall constant which determines the number of electrons, might considerably exceed the true value of $\Delta\mathcal{E}$.

The theory of this problem was developed by Shifrin.

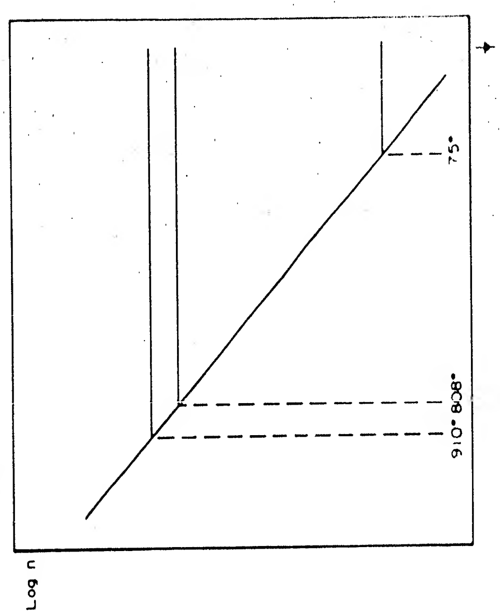
Electroconductivity in Strong Fields

The question of deviation from Ohm's law, observed in strong electric fields, has often been studied on different dielectrics from the theoretical as well as experimental point of view. A strong controversy still exists in the following basic equations, such as:

(1) Is there an area of the fields in which Ohm's law is absolutely true?

(2) Does the number of electrons and their mobility increase in strong fields?

(3) Are additional electrons formed inside the dielectric or on the cathode?


75°
808°
910°
Log n

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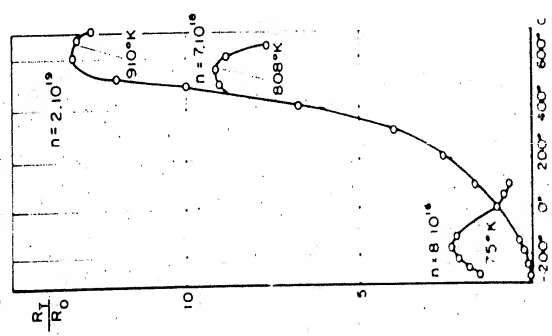
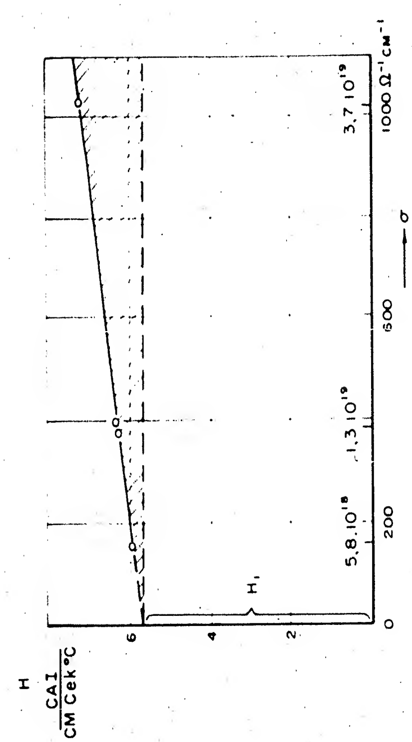

n = 2.10^19
910°K
n = 7.10^18
808°K
n = 8 10^16
75°K
R_T/R_0
10
5
-200
0°
200°
400°
600°

РИС 6


H
CAl / CM Cek°C
6
4
2
0
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600
1000 Ω⁻¹ cm⁻¹
σ
H₁
5,8.10¹⁸
1,3.10¹⁹
3,7.10¹⁹

РИС. 8

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(4) Does an increase of conductivity result in breaking through the dielectric, etc.?

Our investigation, performed together with A. V. Joffe, clarified these questions. The following was ascertained.

The deviation from Ohm's law takes place only at fields E exceeding certain values of E_0. In coordinates E and log σ, we obtained the relation of electroconductivity, σ, for a series of semiconductors in the case of fields with values below E_0, but, for values above that of E_0, log σ always increases linearly with the value of the field.

On observation of the increase of electroconductivity with an increase of the field in darkness or under light, the additional conductivity, $\Delta\sigma$, induced by the photoelectrons could be isolated. The value of $\Delta\sigma$ was found constant or almost constant and identical in the area of weak fields and in the area where the dark conductivity increases quite sharply. This shows that the number of photoelectrons as well as their mobility does not depend on the fields and does not change in strong fields. Therefore, the deviation from Ohm's law is induced by the increase of the number of electrons but not by their mobility, which does not differ from the mobility of photoelectrons.

We could establish that the increase of electron conductivity observed by us in the strong field is not related either to Joule's heat, resulting in heat break-through, or to the mechanism of electrical break-through of dielectrics.

The dependence of the current in the strong field on the temperature and concentration of impurities has been studied. The comparison of

the data with the results of a series of attempts to explain theoretically the effect of the strong fields permitted the evaluation of their importance.

Mechanism of Electroconductivity

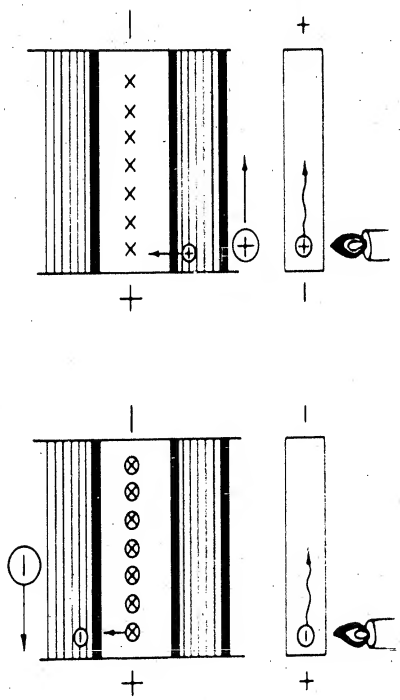
The investigation of the thermoelectrical properties of semiconductors showed that the impurity and the deviation from the stoichiometric formula might change not only the number, but also the sign of the current carriers.

For example, B. Gokhberg and M. Sominsky showed that, in the case of thallium sulfide, the excess of thallium induces an electron conductivity during which the hot end is charged positively as compared with the cold one. The excess of sulfur results in a hole conductivity inducing the negative charge to the hot end. This is shown schematically in Figure 9. The value of the thermoelectromotive force in the first and second case is equal to about 0.7 millivolt per degree.

The directions of the photocurrents in electron and hole specimens of thallium sulfide were observed as opposite. In rectifiers, the forward direction (of easy current flow) reverses during the transition from hole semiconductors to electronic semiconductors.

It seems that the phenomenon also takes place during the electrolysis by a contact.

Therefore, they both indicated contradictions concerning the directions of the currents in the rectifier and photoelements; this led to the question of the sign of the current carriers, but this sign is determined by the nature of the additions. It might be possible that the



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presence of oxygen in air determines the hole conductivity in the materials which contain it in excess.

The sign of the thermoelectromotive force might be used as a very convenient criterion for the determination of the sign of current carriers. In a stoichiometrically composed semiconductor, which does not possess levels other than the filled and the free zone of the crystal lattice, the number of electrons should be equal to the number of holes, and the thermoelectromotive force might appear only on account of the difference between the mobility of holes and electrons.

The changes of thermoelectromotive forces with temperature show the dependence indicated by the theory only in a few cases. This is the reverse dependence on the absolute temperature, as found in, for example, tungsten oxide. In other cases, the thermoelectromotive force was constant, as in the cuprous oxide, or even decreased with decreasing temperatures (as, for example, in vanadium pentoxide at a temperature below -30 C; see Figure 10).

For semiconductors with good conductivity and also semimetals, as, for example, lead sulfide, the value of the thermoelectromotive force and its dependence on the concentration of additions are in very good accord with the theory.

The data concerning the mechanism of the conductivity obtained from the thermal effect almost always coincide with the results of the determination of the Hall effect.

The electric field formed between two bodies by the difference of their contact potential enters the semiconductor and forms in the

boundary layer a space charge like that on the other sign, depending on the sign of the difference of the contact potential.

The theory of this phenomenon was developed by B. Davydov and later by Schottky, and it seems that it was accepted everywhere. An analogous theory of contact layers was proposed by Pekar.

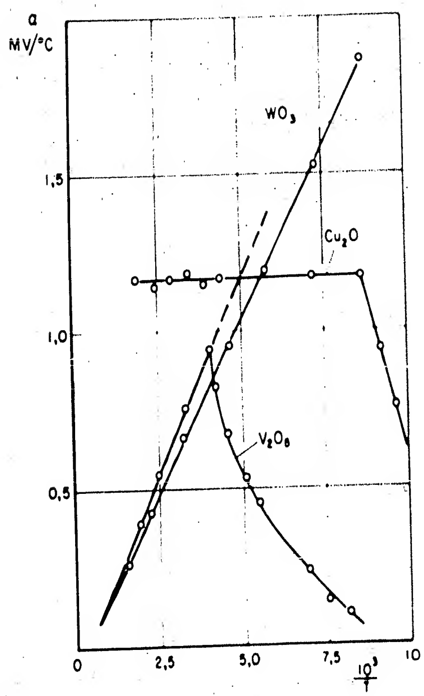
In the case when the contact field leaves the surface layer of the mobile charges, a layer is formed with a sharply increased specific resistance.

Such a layer with low conductivity is formed in the hole semiconductor on the boundary with the metals of lower contact potential (that is, with the lower energy of the electron discharge), as can be easily seen from the scheme of Figure 11, where all four possible combinations are indicated.

In an electronic semiconductor, the barrier layer is formed at the point of contact with the metal possessing a higher contact potential.

In fact, A. V. Joffe observed increased resistance exactly in those cases which were predicted by the theory. The total resistance of the specimen very often increased, even by many orders of magnitude. The theory of Davydov-Schottky indicated that the resistance of the closed (barrier) layer should decrease when the current carriers in the outside field approach the metal, and increase in the contrary case, which results, according to this theory, in the technical rectification effect.

Sometimes a difference in the resistance of the layer for both directions was observed, but the rectification effect was very low, generally between 10 and 20 per cent, and, furthermore, the resistance decreased



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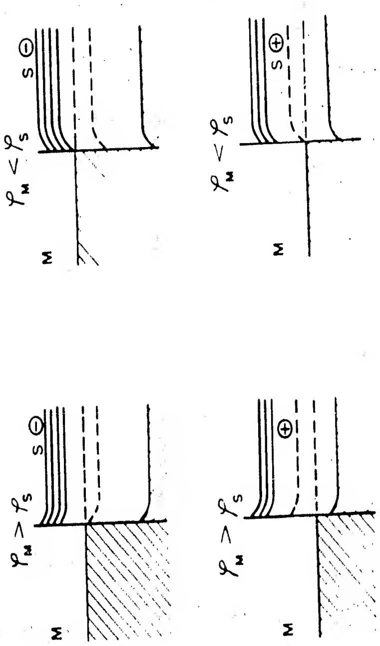

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with the voltage in both directions. An increase of resistance was never observed. The quantitative asymmetry of the current observed in the contact with metal was far from even reaching the coefficient of rectification of the cuprous or selenium rectifier.

It should be remembered that the technology of the preparation of rectifiers and photoelements requires a special treatment of the barrier layer, which gives them the marked rectifying properties indicated. Simple contact with the metal does not form a technical rectifier.

A strongly marked quantitative disagreement with the Davydov-Schottky theory of rectifiers was observed from the point of view of the value of additional resistance, which was determined to be markedly larger than calculated, as well as from the point of view of the thickness of the barrier layer, which quite often was given a value less than 10[illegible] cm, which fact does not have a physical sense.

Despite the prediction of the theory, the relative value of resistance of the layer adjacent to the electrode decreases with decreasing temperature and with decreasing concentration of impurities. The indicated contradictions of the theory with the experimental data do not permit the assumption that the phenomena observed in the boundary layer completely agree with the indicated theoretical picture.

We proposed a hypothesis which has been theoretically developed by B. Davydov and D. Blochinzev, namely, that the rectification effect should take place on the boundary of two semiconductors with different mechanisms of conductivity.

In the direction in which they pass, the electrons of one semiconductor and the holes of the other move toward each other and

recombine themselves (Figure 12); in the opposite direction, the holes and the electrons move in one direction from a common boundary uncovering the layer of lower conductivity, if the time of free existence of the electrons is sufficiently great.

Qualitatively, such an effect is corroborated by our experiments. The quantitative investigation of this phenomenon is not ready yet and makes up our future problems. It is possible that the best solution of this problem, namely, the problem of the rectifier, is the consideration of a combination of both effects: (1) the barrier layer formed by the difference of contact potential already in the absence of the current, and (2) the resistance originating because of different signs of charge carriers with increase of the density of the current in a certain direction.

Photoelectric Phenomena

Determination of the spectral distribution of photoconductivity of the cuprous oxide, performed together with A. V. Joffe, showed that, in the wide spectral interval, photoconductivity is strongly proportional to the number of absorbed photons. Spectral curves of the photoeffect and the location of the maximum depend on the thickness of the investigated specimens.

In cuprous oxide, where the coefficient of absorption decreases with increasing wavelength, the maximum photoeffect is moved in the direction of the short waves according to the decrease of the thickness of the specimen, that is, from 300 microns to 9 microns (Curves 1, 2, 3, and 4 of Figure 13). We could show that the spectral curve of the photoelements

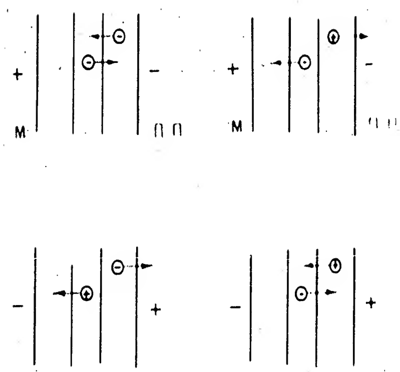

FIG 12

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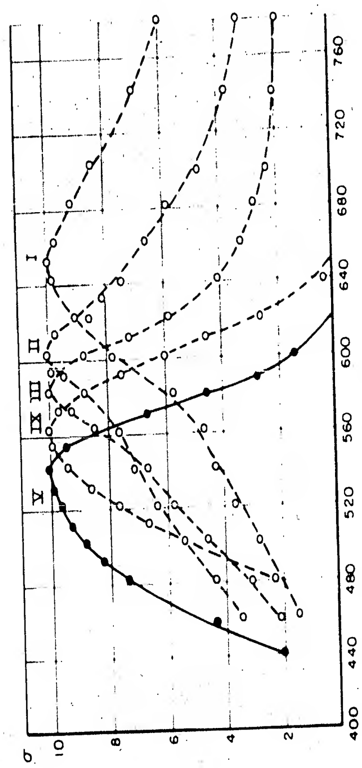

FIG 13

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with a barrier layer (Curve 5) corresponds to the internal photoeffect of the layer with a thickness less than 1 micron, that is, exactly the thickness of such a layer which could still participate in the photoeffect of the barrier layer. Thus could be explained the apparent controversy between the spectral distribution of internal photoconductivity and the photoeffects of the same material.

The investigation of photoelectromotive forces in irregularly lighted monocrystals permitted the assumption of their diffusion equilibria in regions with different concentrations of electrons and gaps. The concentration in the lighted and nonlighted parts of the crystals was measured by the individual pairs of electrodes. The dependence of this effect on the intensity of light, the coefficient of absorption, the temperature, and the photoconductivity of the specimens has been investigated.

I. Kikoin and M. Noskov discovered a new photomagnetic effect. At low temperature in magnetic fields, when the concentration of photoelectrons exceeds the number of thermal electrons many times, irregular lighting induces electromotive forces reaching 15-20 volts. L. Landau explained such photoelectromotive forces as the effect of Kikoin. J. Frenkel developed the theory of "excitons", the diffusion of the state of excitation. This theory, as well as the concept of the diffusion of lattice vacancies, formerly proposed, has been recognized everywhere.

Application of Semiconductors

At present, rectifiers represent the most important applications of semiconductors. A. Levinson and P. Sharavskii improved the technology

of production of cuprous and selenium rectifiers and considerably promoted their industrial production. Besides, B. Kurchatov and A. Dunaev developed a new type of rectifier of cuprous sulfide with magnetic electrodes. The current density of this rectifier is 100 times that of the rectifiers of the two above-indicated types. The technology of production of this new rectifier is much simpler, the dimensions are smaller, and the costs are many times lower. The efficiency coefficient is still not yet high enough, and the method of their connection in a series was not elaborated. The following table illustrates the properties of existing rectifiers:

TABLE 1. RECTIFIERS

	U. S., 1929	Germany, 1937	U.S.S.R., 1938	U. S., 1939
	Cu_2O	Se	Cu_2S	Cu_2S
I/S	0.05	0.04	5	-
I/S with cooling	0.15	0.14	10	5.5
V	8	15	12	5
Coefficient of efficiency	75	75	70	55

In line with commonly used selenium photoelements, an attempt was made, using a semiconductor with a higher photoconductivity, to increase their sensitivity to a greater extent. Such photoelements of thallium sulfide

have been developed by B. Kolomietz, and they possess a sensitivity in the range of 6,000 to 10,000 microamperes per lumen instead of the 500 given by a selenium photocell. Analogous photoelements of Ag_2S are prepared by the Institute of the Physics of the Academy of Sciences of the U.S.S.R. This fact permitted opening up the possibility of applying this new photo-element to sound movies, where it eliminates noises completely and simplifies installation. The efficiency coefficient of the thallium sulfide photo-element reaches 1 per cent. The properties of different photoelements are compared in Table 2 and their spectral sensitivity in Figure 14. In recti-compared in Table 2 and their spectral sensitivity in Figure 14. In recti-fiers, as well as in photoelements, we expect to attain considerable improve-ments by substitution of a good-conducting semiconductor with the correspond-ing mechanism of conductivity and contact potential for metallic electrodes. Some semiconductors of low resistance, as was shown by A. Arsen'eva-Geil, could be used in inductionless voltmeters and as telephone microphones. Such microphones do not induce additional noises and are independent of position. Their resistance changes, in the case of corresponding deforma-tion, are several tenths of 1 per cent. Semiconductors are of very con-siderable interest when used as material for the preparation of thermo-couples. High values of thermoelectromotive force at very low electrocon-ductivity and low thermal conductivity induce much better conditions than does the case of metals.

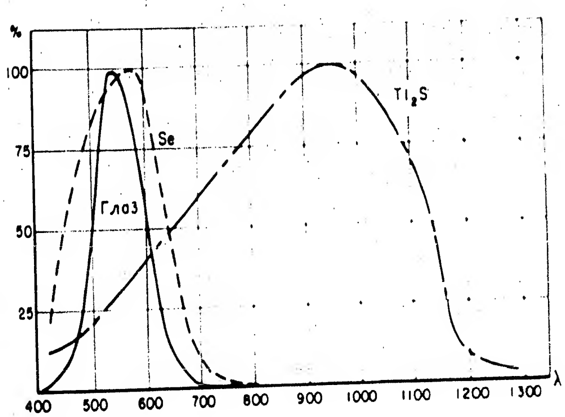
TABLE 2. PHOTOCELLS

	Germany, 1930	Germany, 1932	U.S.S.R., 1937	U.S.S.R., 1937
	Cu_2O	Se	Ag_2S	Tl_2S
I/L	100	400	5,000	10,000
λ	400-600	300-700	400-1300	400-1300
Coefficient of efficiency	0.1	0.04	-	1.1

Fifteen years ago I predicted that, by using semiconductors, the efficiency coefficient could be raised to 4 per cent. This prediction was corroborated by our experiments. The possibility of the production of solid rectifiers is not completely excluded.

Semiconductors are one of the youngest branches of electrotechnique and physics. The engineering possibilities of semiconductors are far from being utilized, and their properties have scarcely been investigated.

The investigation of semiconductors and semimetals is a very important problem; it enables us to enlarge our conception of the electrical properties, not only of semiconductors, but of metals and dielectrics.



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Semiconductors and semimetals of low resistance are of particular interest. In fact, in all engineering applications of semiconductors (in rectifiers, thermocouples, and thermistors), the internal resistance hampered the effect of those elements very much, decreasing the coefficient of efficiency of the entire apparatus.

From another point of view, the properties of electrons, which are located on the boundary of the region, and the generation and entry from this region at an easily obtained temperature present considerable interest in themselves, as well as in the comprehension of the properties of such low-conducting metals as, for example, bismuth, antimony, silicon, etc.

Despite this fact, up to the present only the group of semiconductors bordering insulators, having a specific resistance of 10^2 to 10^{12} ohm-cm were investigated. Concerning semiconductors with resistances in the range of 10 to 10^{-3} ohm-cm, there are only very occasional data, which do not even permit evaluation as to whether such substances are semiconductors or semimetals. Furthermore, the alloys of semiconducting metals have not been investigated.

Fused (fluid?) electron semiconductors have not been investigated either. The first series of our investigations already show several new facts of primary importance to the theory of the fluid state.

Investigation of the phenomena on the borderline of two semiconductors represents not only a theoretical but also a considerable practical interest. If the nature of rectifiers and photoelements could be assumed as resulting from the properties of the barrier layer, then, as our

experiment showed, these properties are particularly marked between two semiconductors with different signs of the current carriers.

Furthermore, as electrodes for photoelements, oxide and sulfide semiconductors are much more stable from the point of view of outside influence and corrosion than pure metals. With the same transparency, they are mechanically more resistant than semitransparent layers of metal.

The time of the free existence of the electron is of major importance for photoeffects, as well as for the phenomena of rectification. In the thermocouple, the electrodynamic forces of semiconductors of different sign of conductivity are summarized, and, to a great extent, increase the effectiveness of the thermocouple. The possibility of changes in concentration of the free charges and the temperature curve of the conductivity opens a wide future field. This problem, together with the question concerning the energy equations of electrons and the electrization of the contact, will be the subject of our investigation in the near future at the Physico-Technical Institute of the Academy of Sciences of the U.S.S.R.

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1. Conductivity
2. Bombardment-Induced Conductivity
3. Magnetoresistance
4. Rectifiers (Diodes)
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IV. COMPOUNDS

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